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AEROSPACE GROUND EQUIPMENT'S
IMPACT ON AIRCRAFT
AVAILABILITY AND DEPLOYMENT

THESIS

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THESIS

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I wish to apologize to the reader in advance for any errors discovered in this thesis. I take full responsibility for any that may exist.

<div align="right">Jeffrey D. Havlicek</div>

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List of Acronyms and Abbreviations

ACC	Air Combat Command
ADPS	Automated Data Processing System
AF	Air Force
AFB	Air Force Base
AFCQMI	Air Force Center for Quality Management Institute
AFIT	Air Force Institute of Technology
AGARD	Advisory Group for Aerospace Research and Development
AGE	Aerospace Ground Equipment
ANOVA	Analysis of Variance
ASC	Aeronautical Systems Center
CALM	Computer Aided Load Manifesting
CASE	Computer Aided Software Engineering
CGAC	Combined Generator Air Conditioner
CI	Confidence Interval
COMPES	Contingency Operations/Mobility Planning and Execution System
DoD	Department of Defense
FY	Fiscal Year
IMDE	Integrated Model Development Environment
JSF	Joint Strike Fighter
LANTIRN	Low Altitude Navigation Targeting Infrared for Night

LCOM	Logistics Composite Model
LOGDET	Logistics Detail
MAGSS	Multifunction Aircraft Ground Support System
MASS	Multifunction Aircraft Support System
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NATO	North Atlantic Treaty Organization
NMC	Not Mission Capable
OOP	Object-Oriented Programming
PCM	Percent of Canceled Missions
SPO	System Program Office
SSE	Sum of Squared Error
USAF	United States Air Force
UTC	Unit Type Code
WUC	Work Unit Code

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ABSTRACT

The first purpose of this thesis was to study the effects of four factors on aircraft availability: the aerospace ground equipment (AGE) design configuration, the mean time between failure (MTBF) of AGE, the mean time to repair (MTTR) AGE, and the travel time to transport the AGE around the flightline. A simulation developed by Carrico (1996) that has its foundation based on the Logistics Composite Model (LCOM) was used. ANOVA results indicated that the present estimates of these factors are too broad for trade studies that include an estimate of aircraft availability to begin. The time it takes AGE to travel from one place to another around the flightline strongly affected aircraft availability. It is recommended that further AGE field observation and data collection be accomplished before the merits of one AGE cart technology is compared to another.

The second purpose of this thesis was to collect as much information on the deployability and affordability of AGE as possible. Although much of the information collected was a few years old, the results suggest that new technologies improve the deployment footprint and the combined acquisition and deployment costs.

Background information about support equipment and AGE is included in the study.

AEROSPACE GROUND EQUIPMENT'S IMPACT ON

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I. INTRODUCTION

New Challenges for the United States Air Force

Two of the core competencies of the United States Air Force are Agile Combat

Support and Rapid Global Mobility. These competencies support an Air Force that seeks

to engage in missions anywhere in the world with minimal warning and preparation.

Indeed, the events in Somalia, Haiti, and Bosnia reflect a new world order where the

location of future military operations are highly uncertain. Gone are the days when

massive stockpiles of war reserve equipment could be pre-positioned at the anticipated

battlefield location. Furthermore, fewer troops are being stationed overseas (Table 1)

because of national budgetary constraints and strained foreign relations. As an example,

Japan, one of our long standing forward staging areas to the Pacific and the Middle East,

is becoming increasingly inaccessible. Okinawa, Japan's southernmost island, is host to

over 28,000 U. S. troops (Mallaby, 1996:17). Recently however, Okinawa's governor,

Masahide Ota, has declared that all American troops should leave and he has the support

of nine out of ten Okinawa voters that agreed that American presence in Okinawa should

be reduced (Mallaby, 1996:17). This sentiment has forced the U. S. to agree to return 21

percent of all land used by the U. S. bases on Okinawa to Japan by the year 2008 (Evers,

1996:3).

Table 1 clearly indicates that the number of military personnel in foreign countries is decreasing in both number and proportion. This trend of reducing the forward staging of our U.S. military encourages an emphasis on rapid response of our military from the U.S. to anywhere in the world. As a response to this challenge, new military force packages, like the Air Expeditionary Force, which seek rapid deployment of forces with minimal logistics requirements, were exercised with deployments to Bahrain, Qatar, and Jordan in 1996 (Department of the Air Force, 1997:1). However, the costs of moving traditionally large force packages has resulted in plans of early decommissioning of the C-141 due to overuse and increased funding for the C-17.

Table 1. US Armed Forces in Foreign Countries

Year	Military Personnel in Foreign Countries (MPIFC)	Total Active Duty Military Personnel (TADMP)	MPIFC/TADMP (%)
1984	511		
1985	515	2151	23.9
1986	525	2169.1	24.2
1987	524	2174.1	24.1
1988	541	2138.2	25.3
1989	510	2130.2	23.9
1990	609	2069.4	29.4
1991	448	2002.6	22.4
1992	344	1806.1	19.0
1993	306	1705.1	17.9
1994	287	1610.5	17.8
1995	238	1518.2	15.7
1996		1481.7	
1997		1457	
Source: (Department of Defense, 1996b)			
1996	240	1471.7	16.3
Source: (Department of Defense, 1996a)			
All personnel levels in thousands and collected at the end of the fiscal year			

Support Equipment Challenge Airlift Reduction

One method of improving the mobility of our aerospace forces and decreasing the

airlift required to deploy them is by reducing the amount of support equipment necessary

to maintain and operate U.S. aircraft abroad. Consider the magnitude of the support

equipment problem as expressed in a report by Northrop Corporation (Aeronautical

Systems Center, 1993:2):

> *USAF [United States Air Force] tactical air power was*
> *dependent upon strategic airlift to move the required support*
> *equipment for deploying squadrons/wings. Approximately 28*
> *USAF squadrons of fighter and attack aircraft were deployed*
> *requiring an estimated 390 C-141 equivalent airlift sorties.*
>
> *Most of the cargo initially deployed with tactical air force*
> *units was comprised of personnel, support equipment, and the*
> *spare parts needed to prepare aircraft for combat sorties and*
> *repair them when components malfunction. An estimated 17.5*
> *million pounds and 1.8 million cubic feet of support equipment and*
> *supplies were airlifted to support the initial deployments of these*
> *tactical forces. Although they constituted a small percentage of*
> *the total airlift missions flown to the theater, these 390 sorties*
> *were flown primarily in the early phase of Desert Shield. Any*
> *action that can be taken to reduce these early USAF airlift*
> *requirements will free up strategic airlift assets for other DoD*
> *[Department of Defense] priorities.*

Any serious reduction of support equipment should consider the effects of Aerospace

Ground Equipment (AGE) since AGE accounts for a large percentage of the deployed

equipment transported by airlift to a deployed location. As an example, consider the

366th Composite Wing's distribution of weight in their deployment package (Figure 1,

Source: Aeronautical Systems Center; 1996:7). Twenty-two percent of all deployment

weight is attributable to AGE carts of a type that this report will be investigating. An

additional 55% of all weight is attributable to other flightline equipment. Much of this

other flightline equipment is either wheel-less AGE or the maintenance manuals, tools, testers and other equipment used to support AGE.

MRSP 8%   Eng Spares 4%

Personnel 11%

Rolling Stock 22%

Other Flightline Equip 55%
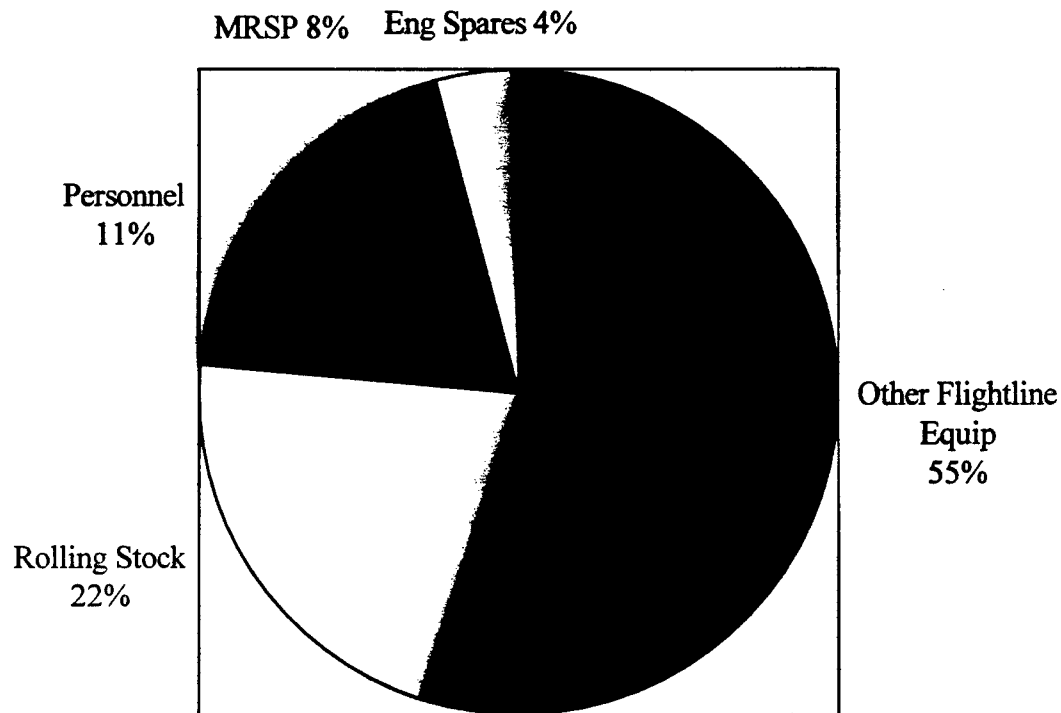
Figure 1. 366th Wing Deployment Weight Distribution

Traditionally, AGE was developed to satisfy a specific maintenance requirement like air conditioning, hydraulic pressure, or electrical power. This led to an entire fleet of carts being required to satisfy the maintenance requirements of a single squadron of deployed aircraft. The result created a package similar to that shown in Figure 1 where rolling stock and flightline equipment (mostly AGE or AGE support equipment) comprise the majority of all deployed equipment. A reduction in the amount of AGE required could cause a significant reduction in the deployment footprint.

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AGE Reduction as an Opportunity

The idea of scaling back AGE requirements is not new. As far back as April 1992, Headquarters, Strategic Air Command, commissioned an operational feasibility study of a single cart that could satisfy multiple needs (Wakefield, 1992). Furthermore, the Advisory Group for Aerospace Research and Development (AGARD), a committee of the North Atlantic Treaty Organization (NATO) studied and ranked 87 technologies and procedures on their affect of increasing the mobility of combat aircraft. The panel selected the reduction and combination of AGE as one of their top three short-term improvements to improving the mobility of NATO air forces (Field, 1993:Sect. 6.1). The 1996 Air Mobility Master Plan included the following vision about its AGE (Air Mobility Command, 1997: 5-59):

> *Weapon systems today require unique support equipment.*
> *Much of our existing support equipment is bulky and performs a*
> *single function. Over the years, follow-on buys have resulted in*
> *many different manufacturers for the same type of equipment,*
> *creating a large logistical trail of parts, special tools, and*
> *technical manuals to accompany deployed equipment. To minimize*
> *the number and type of assets moved during deployments, AMC*
> *will look for units which can support several different weapon*
> *systems. These units will be multi-functional, such as supplying air*
> *conditioning, electrical power, and ram air for engine starts.*

Originally, the F-22 System Program Office (SPO) intended to replace some of the AGE requirements with systems that would be located onboard the aircraft. These goals are in agreement with the long-term recommendations of AGARD (Field, 1996:6.1.2). Weapons Bay and Avionics-bay lighting and an Auxiliary Power Unit capable of meeting maintenance needs were once envisioned (Kramer, 1997). However,

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technological, weight, and space limitations have forced most of the AGE functions back to ground-based support equipment or have rendered the remaining on-board systems insufficiently powered to replace traditional AGE carts for most maintenance applications (Kramer, 1997). In fact, present estimates show a number of AGE carts for the F-22s will be larger and heavier than some of the equivalent carts needed for a squadron of F-15s or F-16s primarily because the AGE being used is identical to the units used for bombers and airlifters. For example, the A/M32A-86D generator, most commonly used on bombers and airlifters, will probably be required in place of the lighter A/M32A-60 generators needed by the F-16 and F-15 (Technically speaking, each F-16 squadron does have a single A/M32A-86 authorized, but its primary use is for AGE service and not for aircraft service) (Kramer, 1997). Also, the A/M27T-13 hydraulic cart, developed for the B-2 and C-17, will weigh 6,500 pounds which is over 1,900 pounds more than the MJ-2A used by the F-16 (Kramer, 1997). Although the F-22 hydraulic carts have more capability than the F-16 carts (Kramer, 1997), the increase in capability is only being required due to the increased needs of the F-22 for AGE. Such a trend of escalating AGE requirements may force a fighter squadron to be less and not more deployable in the future. In all fairness, bottom-line deployment package size for all support equipment categories are far more promising. Where the F-16 requires 18 C-141 to deploy, the F-22 will require only 8 (Kramer, 1997). However, these reductions are primarily implemented through decreases in support equipment categories other than AGE. For instance, the two-level maintenance concept has reduced the need for flightline test

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equipment and backshop repair equipment (Kramer, 1997). Although support equipment reduction success stories abound in the F-22 SPO, AGE cart reductions aren't as great.

The Joint Strike Fighter (JSF) SPO has renewed the crusade of a reduced deployment footprint. The JSF SPO initially identified three areas of interest involving AGE during the system design phase:

1. On-board oxygen generation,

2. On-board power and cooling, and

3. The use of advanced ground equipment (Griffis, et al., 1997:4).

Certainly, these long-term goals are desirable for many reasons, but the failure of all other aircraft designs to accomplish this set of objectives indicates the difficulty of this task and the challenge that awaits the JSF SPO.

One compromise between the acquisition of 1950's-designed AGE carts and the futuristic aircraft that may have all AGE-provided services onboard is a multifunction aircraft support system (MASS). The creation of a prototype MASS cart is being funded by the Logistics Resource Directorate of Armstrong Laboratory, Human Resource Division. Their goals are to understand the operational requirements for present and future aircraft and to create a new generation of AGE that increases the supportability and reduces the deployment footprint of AGE (Boyle, 1997:1). Research efforts have included identifying the maintenance processes that use AGE and the physical design of AGE carts. The lab's research addresses the processes used by present and future AGE. Their goal is to create future AGE carts that can perform multiple functions.

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Previous research efforts have focused on understanding how base-level aircraft sortie generation processes interact. Rand and the Air Force Logistics Command developed the Logistics Composite Model (LCOM) in 1968 as an effort to provide a simulation-based decision support system and used test data collected in South Vietnam during first half of 1967. Their goal was to create a model that could be used to test the effectiveness of changes in operational and logistical policies (Fisher, et al., 1968:2-3). This model has been in almost continuous review and improvement ever since. In fact, many subsequent models have either used LCOM as input to their own model or as a verification/validation of their own model's functionality.

Recent research funded by the Logistics Research Directorate of Armstrong Laboratory has sought to improve the resolution of LCOM to understand AGE-specific issues. The first simulation study completed was by TASC, Inc (Zahn, 1995; Carrico, 1996). The second was by Battelle (Walters, 1996). This thesis project is the third simulation study under the direct sponsorship of the Logistics Research Directorate of Armstrong Laboratory.

Problem Statement

Plans are being made to create the first new generation of AGE carts in decades. These new carts must meet the long-term goal of efficiently supporting the maintenance needs of aircraft while also meeting new requirements in areas like environmental compliance and airlift deployability. Ideally, a complete trade study of each AGE design option would be commissioned to compare operability, reliability, maintainability, affordability, deployability, and environmental impact all in one integrated analysis.

Unfortunately, the present state of AGE design research is not at a level where meaningful data exists for such a study to be performed. This thesis attempts to bridge part of the gap between the present state of this field and the state necessary to perform such an in-depth analysis. The purpose of this research is twofold. The first purpose is to identify what aircraft availability factors need more precise estimates before adequate aircraft availability comparisons of the percentage of canceled missions (PCM) are possible. An explanation of PCM is necessary. By PCM, I mean the planned two-ship missions that were canceled due to unavailable aircraft. The number of planned missions in a day is based on the schedule. Chapter III includes a discussion about the schedule used for this research. PCM was chosen as the preferred metric over the more commonly used Not Mission Capable (NMC) rating. This decision was based on the consideration that NMC does not provide any information on the impact of the downtime. Potentially, two squadrons could have the same 15% NMC but have drastically different effectiveness if the first squadron managed all aircraft downtime in the dead of the night while the second squadron incurred all of its down time in the busiest flying portion of the day.

In an effort to satisfy the first purpose of this thesis, the estimated range of the following factors are varied:

1. Types of AGE carts included in the deployment package

2. Failure rates of AGE carts by cart type

3. Time to repair AGE carts

4. Travel time from aircraft to aircraft or to the AGE shop

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The goal is to see if present high and low estimates of each factor cause statistically and relatively significant differences in the estimated PCM. If they do, then further research is recommended to determine a tighter range for the factors found to be significant. If they do not, then a tight-enough range for these factors has been found and trade studies that include aircraft availability can begin.

The second purpose of this research is to evaluate each AGE package in a more holistic approach. Carrico (1996) developed the correct size of future AGE packages in terms of aircraft availability only. Deployability was only briefly considered. An objective of this thesis is to see the results of a specific design configuration in terms of several performance measures.

Three sets of measures of effectiveness were collected for each configuration:

1. Aircraft availability defined as Percentage of Canceled Missions (PCM) under surge conditions

2. Deployability defined as the required floor space, volume, and weight to deploy AGE

3. Affordability defined as the total AGE costs based on unit prices and airlift costs

The different treatments resulting from the manipulation of the factors identified above are considered in terms of these criteria.

Research Questions

Using present range estimates as levels for our factors, do statistically and practically significant differences in the expected PCMs exist?

The intent of this line of questioning is to focus on whether present estimate ranges for the identified factors are close enough to cause a single prediction of PCM or if the estimate ranges are still so wide that a decisive answer on the expected PCMs is not yet possible.

What is the deployment footprint for each AGE design option?

The new MASS designs are intended to reduce the amount of airlift required to move a squadron of aircraft to a new base of operations. The most current estimates of how much space and weight the different options would require are identified.

What are the unit costs of the AGE carts and the airlift costs involved with each alternative?

Rough costing information is provided for the total unit costs of the AGE cart package as are rough cost estimates for the cost of airlift needed to transport the AGE carts to an overseas location.

Which options are efficient in overall value?

Cost, deployment footprint, and PCMs are all combined in a single presentation. The reader must be cautious regarding the interpretations of these results since PCMs are susceptible to errors caused by inaccurate assumptions.

Research Hypothesis

The null hypothesis is that all of the AGE-related factors will cause no differences in estimates for PCM, acquisition costs, or deployment size. The alternate hypothesis is that at least one of the factors will cause statistically and/or practically significant differences in PCM, cost, or deployment size.

Methodology

This research was conducted in phases. They are:

1. *Estimate aircraft availability of each treatment using a simulation model*

2. *Identify which factors are statistically significant*

3. *Calculate the airlift requirements for each treatment*

4. *Calculate the costs for each treatment*

5. *Evaluate each treatment in terms of its aircraft availability, deployability, and acquisition costs profile.*

Assumptions

This research assumes a future need for AGE carts. However, acquisition programs such as the Joint Strike Fighter are working towards on-board aircraft systems like the On-Board Oxygen Generation System (OBOGS) and the Auxiliary Power Unit (APU) that would reduce the need for ground-based support equipment (Griffis, et al., 1997:4). Although research into new aircraft systems may prove extremely fruitful in reducing logistics deployment requirements, historical acquisition results show that

logistics support systems are often the first units to be removed from an aircraft when performance specifications are not being met. Progress is being made as the latest powered AGE estimates from the F-22 SPO demonstrate (Table 2). However, many bulky, heavy, mostly single function AGE carts will continue to be required in the foreseeable future.

Table 2. Table of Allowance, F-16 vs. F-22

Powered AGE Cart	Number Required for 24 F-16 Squadron	Number Required for 24 F-22 Squadron
Air Conditioning Cart, Diesel (F-22 also includes multifunction of liquid cooling)	10	3
Air Conditioning Cart, Electric (F-22 also includes multifunction of liquid cooling)	2	3
Generator Cart	12	3
Power Converter Cart	NA	3
Nitrogen Servicing Cart (F-16 uses 2 different types)	5	4
NF-2D Floodlight Cart	12	9,
Hydraulic Test Stand, Diesel	3	3
Hydraulic Test Stand, Electric	3	1
Low Pressure Air Compressor	6	2
Total	53	31

Source: F-16 Table of Allowance-316 and draft F-22 Allowance Standard-222 as identified by Kramer, 1997:3

In Chapter III of this thesis it is explained that reliability data on the MJ-2A hydraulic servicing cart was unavailable and that the reliability data for a TTU-228 hydraulic test stand cart was used instead. An implicit assumption in this procedure is that the two hydraulic-based carts have similar maintainability characteristics. Likewise, the reliability data for the Combined Generator / Air Conditioner (CGAC) was also unavailable. However, the CGAC should be at least as reliable as the Multifunction Aircraft Ground Support System (MAGSS) since the MAGSS was designed first and is far more complex in functionality than the CGAC. Therefore, MAGSS data was used for the reliability of the CGAC unit.

Although the estimates of mean MTBF and MTTR for AGE carts were available from literature, the population distributions were not. Therefore, this thesis used the lognormal distribution for AGE MTBF and MTTR just as Carrico (1996) and Zahn (1995) had done. The variance was set at ten percent of the mean.

Scope/Limitations

This study provides a general analysis approach that could be applied to any weapon system. However, results are developed using the aircraft maintenance records of an 18-aircraft F-16 squadron. The F-16 platform is specifically well-suited for our analysis since the two largest aircraft research and developmental programs of this decade are the F-22 to replace the F-15 and the Joint Strike Fighter to replace the F-16—both fighters that are similar to the F-16 in many regards. These two programs are the most-likely beneficiaries of future AGE improvements. Future analysis projects could be readily performed as other weapons system databases are adapted to follow this thesis's methodology.

Models were not built specifically for this research. Instead, previous work in the field of AGE modeling was enthusiastically used. The AGE failure and repair rates come from a report by Battelle, Inc (Hale, 1996:18-19). AGE usage and specific modeling procedures were developed by TASC, Inc. for Armstrong Laboratory (Carrico, 1996; Zahn, 1995) using the Integrated Modeling Development Environment (IMDE). An excellent matrix of the AGE usage assumptions for each work unit code (WUC) can be found in the report by Carrico (1996:39-91). All other input estimates and modeling procedures are developed using the LCOM. Only minor alterations (such as varying the

estimates of distribution parameters) to the existing models were performed. Although this limits the selection of factors to those available in the existing models, the added benefits of cross comparison of the results of this study to previous study results outweigh this limitation.

This research treats AGE failures at the system level for each AGE type. Future research could perform component-level failure mode analysis and then apply the results by increasing the level of detail in the model.

This study's analysis of how AGE influences the sortie generation system is primarily about how the design, reliability, maintainability, and availability of the AGE system influences the availability of the aircraft. Deployability and cost issues are also discussed. The treatment of deployability and cost is considered only in terms of cost and physical dimensions of a specific package of equipment.

The results and conclusions of this thesis should be tentatively applied to AF decision making. The results based on the squadron of F-16s may not be similar enough to the F-22 or JSF to be unilaterally applied to decision making within these programs. However, the fundamental methodology could be easily adapted to change the F-16 specific information into the predicted F-22 or JSF estimates. This conversion would require identifying how often various WUC are performed, how long they take, and which maintenance jobs require AGE. The results may or may not be similar to the matrix used for the F-16. Then, the new results would have direct applicability to these programs.

Management Implications

The results of this thesis should provide ample opportunities for further support equipment decision making and research. Hopefully, the results will focus the support equipment community on areas that need more attention. Subsequent managerial actions may include (but are not limited to):

- Additional field research to develop more realistic modeling processes

- Additional field research to develop better estimates of factors identified as causing statistically or relatively significant differences in PCM

- The design and experimental testing of the most promising MASS design packages

Organization of the Thesis

This chapter has presented the reader with the environment of the research, the problem statement, the research objectives, the hypothesis, the scope, the limitations, and the managerial implications of the research. Chapter II provides in-depth information on previous research in this field. Chapter III details the methods used to answer the research questions that satisfy the research objectives. Operational definitions of research concepts are included in both Chapters II and III. Chapter IV includes the research findings as well as some intermediary results regarding the application of the methodology. Chapter V is a discussion of conclusions, recommendations, and suggestions of future research efforts.

II. PREVIOUS RESEARCH

Introduction

Unlike the previous chapter that discussed the motivation of studying the effects of AGE-configuration on AF operations, this chapter discusses the relationship of previous research to the methods of this study. The discussion begins by focusing on AGE and concludes with a discussion of analytical and simulation models relevant to the methodology used.

Support Equipment

The purpose of support equipment is to sustain in a cost-effective manner the designed maintainability parameters of the system (such as Mean Time To Repair (MTTR) and Mean Time Between Failure (MTBF)) (Langford, 1995:445). Several definitions of what constitutes support equipment are available. The following are suggested:

> *Any item of equipment required to support operation or maintenance.* (Jones, 1987:92)

> *Tools, metrology, and calibration equipment; monitoring and checkout equipment; maintenance stands; and handling devices that are categorized into special and common types. It also includes production test or support equipment that is modified for field use.* (Green,1991:14)

> *All equipment (mobile or fixed) required to support the operational and maintenance requirements of the system including ground handling and maintenance equipment; tools, metrology and calibration equipment; and manual and automatic test equipment.* (Przemieniecki, 1993:266)

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The tools, special monitoring, diagnostic and check-out equipment, metrology and calibration equipment, maintenance stands and servicing and handling equipment required to support scheduled and unscheduled maintenance of the end product.
(Finkelstein and Guertin, 1988:122)

All equipment required to make a weapon system, command and control system, support system, subsystem, or item of SE operational in its intended environment. This includes all equipment required to install, launch, arrest (except Navy shipboard and shore based launching and arresting equipment), guide, control, direct, inspect, test, adjust, calibrate, appraise, gage, measure, assemble, disassemble, handle, transport, safeguard, store, actuate, service, repair, overhaul, maintain, operate, arm, or rearm the system, subsystem, end item, or component. This definition applies regardless of the method of development, funding, or procurement (special purpose); within these two categories, developmental (no Government-approved specification/drawing) and standard (with Government-approved specification/drawing) subcategories may exist. If this SE is used on an Aircraft or Missile weapon system, then it is a MILHDBK-300 item. NOTE: The following equipment is excluded from the definition of support equipment:

1. *Common powered and manual hand tools.*
2. *Housekeeping items.*
3. *Office furniture and equipment and items common to all activities defined in applicable allowance lists that are required as indirect support.*
4. *Common production tools and tooling such as lathes, drills, presses, plating equipment, grinders, and induction heaters.*
5. *Items used only by the contractor.*
6. *Personal equipment (e.g., headsets, microphones).*
7. *Off-line automatic data processing (ADP) equipment.*
(Department of Defense, undated)

Many types of support equipment exist. Although various labels have been created to classify different types of support equipment, no classification taxonomy exists. However, some of the most commonly used classifications:

- *Common Support Equipment (CSE)*: any item of support equipment that is currently used by the military and has multiple applications. (Jones, 1987:93)

- *Special Support Equipment/Peculiar Support Equipment (PSE)*: items of support equipment that have limited application, or that have been developed to perform a specific support function for a single weapon system. (Jones, 1987:93)

- *Test Equipment (TE)*: support equipment used during the process of identifying failures of the weapon system or its components. (Jones, 1987:97-98)

- *Powered Support Equipment*: an item of support equipment that requires power to operate.

- *Aerospace Ground Equipment (AGE)*: support equipment used on the flightline to support aircraft maintenance requirements.

- *AGE cart:* Powered or unpowered AGE that typically rolls on wheels. This does not include AGE stands with coasters or wheels.

- *Rolling Stock*: Support equipment that is rolled onto an airlifter directly instead of being loaded first onto a 463L pallet and then loaded on an airlifter using material handling equipment. Most AGE carts are one type of rolling stock.

Support Equipment Management Philosophy

Life cycle cost is supposed to drive support equipment acquisition in the Air

Force since support equipment allows for maintenance work to be accomplished less

expensively than without it (Langford, 1995:448-451). The following excerpt from a

document in the Air Force Acquisition Model (Department of the Air Force, 1996a)

explains the Air Force philosophy of support equipment procurement:

> *The SE manager must be the advocate for the support community to ensure that overarching principles such as deployability and avoiding the proliferation of new support equipment are included in the program events and consideration that will lead into the next program phase.*
>
> *It's important to establish, early in the acquisition, a strategy to address the support equipment requirements, as they are initially outlined in the Program Management Directive (PMD) and have a major impact of program life cycle cost and deployability. The SE Manager can influence the emerging SE strategy by advocating a weapon system design that minimizes overall SE needs, maximizes the use of existing SE and handtools, and that eliminates as much as possible the need to develop new SE unique to the weapon system.*

Although this policy sounds very reasonable, it is the opinion of this thesis's author that

the goal has often been misapplied. Instead of developing the best performing systems at

the lowest price with the smallest deployment footprint, many support equipment

managers have focused on the reduction of new support equipment as the primary method

of implementation. As such, new equipment is viewed poorly before a proper review of

whether the new equipment outperforms the existing systems at a lower life cycle cost

and a reduced deployment footprint.

Aerospace Ground Equipment (AGE)

Aerospace Ground Equipment (AGE) is a particular class of support equipment that provides a maintenance service to an aircraft. The service provided may be hydraulic pressure, heat, air conditioning, light, pressurized air, etc. AGE cart descriptions are available (Tovrea, 1997; Hale, 1996). The following tables list current AGE and the estimated amount of hours of labor per month required to inspect and repair the AGE cart (Department of the Air Force, 1996b:17-18). An explanation of the importance of inspection and repair estimates is discussed in Chapter III.

Table 3. List of Powered AGE

Name	Man-hours/month/item
Turbine Generator	18.96
Diesel Generator (Large)	25.08
Diesel Generator (Small)	3.26
Motor Generator	5.55
Light Stand	13.86
Heater	13.22
High Powered Air Compressor	10.08
Low Powered Air Compressor (Diesel)	5.42
Low Powered Air Compressor (Electric)	3.99
Turbine Compressor	9.22
Cabin Leak Tester	7.19
Diesel Hydraulic Test Stand	51.23
Air Conditioner (Diesel)	22.39
Air Conditioner (Electric)	4.89
Air Recycler Air Conditioner	7.55
Motor Hydraulic Test Stand	6.40
Load Bank	9.97
Powered Maintenance Stand	11.54
Deicer	11.76
Blower/Vent	1.46
Bomb-lift Truck	17.12
Hydraulic Jacking Manifold	8.10
Miscellaneous	5.29
Electric Bomb-lift Truck	11.30
Large Munitions Trailer	96.45
Small Munitions Trailer	64.30

Table 4. List of Non-powered AGE

Non-Powered AGE	Man-hours/month /item
B-1/2/4 Stand	5.57
B-3/7 Stand	18.93
B-5/C-9 Stand	7.62
B-6 Stand	10.36
Aero Med Stand	2.54
C-1 Stand	0.89
C-5 Towbar	12.78
C-97/135/118/121 Tow Bar	6.24
C-124/133/DC-8 Tow Bar	5.27
Helicopter Tow Bar	1.96
T-38/F-5/T-39 Tow Bar	2.54
T-33/T-37 Tow Bar	1.46
B-52 Tow Bar	16.57
Nitrogen Cart	3.42
Oxygen Trailer	4.45
General Purpose Trailer	1.95
Hoist Frame	3.13
Aircraft Jacks	3.12
AMS-01 Maintenance Stand	4.43
VIP-01 Board Stand	10.04
VIP-01 Board Stand without Motor	5.79
Drag Chute Stand	10.81
Fuel Bowser	5.53
Oil Servicing Cart	3.00
Liquid Nitrogen Cart	15.41
Engine Run Fence	2.91
Wash Cart	7.50
Miscellaneous	5.29

NOTE: If AGE maintainers are expected to service the aircraft and transport the AGE back and forth from the AGE shop to the aircraft, then the work standard recommends adding an additional 5.29 hours to each estimate above.

It should be noted that not all types of AGE are needed to support an aircraft type. Usually only a subset of AGE equipment is needed at a specific base. Since this study looks only at the AGE needs of an F-16, only the AGE necessary to support a squadron of 18 F-16s was investigated. Furthermore, this thesis limited the equipment studied within the model to the few AGE items that are used most often by maintenance personnel. These are all AGE carts and are identified in Table 5. The table lists the name of the item, the military's technical name, and the number of pieces authorized at a few different

bases—including the Headquarters, Air Combat Command, standard requirement. The number of AGE items that were used in the AGE studies by Carrico (1996) and Zahn (1995) are also listed.

Table 5. AGE Allowances for 18 Aircraft F-16 Squadron

AGE Cart Name	Tech Name	Hill	Mt	178th	ACC	Carrico	Zahn	Weight (lbs.)	Volume (cu. ft.)
High-Pack Compressor	MC-1A	2	1	2	1	2	2	2000	179
Low-Pack Compressor	MC-2A	4	7	8	4	8	4	890	109
Nitrogen Cart	N2 Cart	3	2	2	2	2	3	3340	252
Cooling Air	AM32C-10	9	8	8	9	8	9	1290	302
Power Generator	AM32A-60	9	8	9	9	8	9	3340	286
Hydraulic Pressure	MJ-2A	2	2	4	2	2	2	5100	438
Lighting	NF2D	14	10	12	9	14	14	2280	269

Source: Carrico, 1996:18 and Zahn, 1995:1195.

The information from Carrico (1996) and Zahn (1995) can be compared to the information obtained from the Logistics Detail (LOGDET) Data within F-16 force packages in the Contingency Operation/Mobility Planning and Execution System (COMPES) Logistic Module-Base Level (LOGMOD-B) database. These force modules are grouped together by a code called a Unit Type Code (UTC) and are meant to describe the standard equipment expected to deploy with the operational unit. Reviewing the LOGDET for F-16 UTCs reveals the following AGE equipment is scheduled to accompany a squadron of 18 F-16 LANTIRN aircraft (Tables 6 and 7).

Table 6. Individual AGE Cart Allowances for 18 F-16s in COMPES

AGE Cart Name	Quantity	Weight (lbs.)	Length (in.)	Width (in.)	Height (in.)	Volume (cu. ft.)	Area of Floor Space (sq. ft.)
Lighting	9	2280	108	68	67	285	51.00
Power Generator	9	3120	123	62	68	301	52.96
Cooling Air	9	1380	108	71	69	307	53.25
Low-Pack Compressor	4	820	92	58	41	127	37.06
Hydraulic Pressure	2	7750	144	72	79	474	72.00
High-Pack Compressor	1	1980	88	67	60	205	40.94
Liquid Nitrogen Cart	2	3400	126	60	55	241	52.50
Gaseous Nitrogen Cart	1	3400	126	60	55	241	52.50

Source: Department of the Air Force, 1995.

Table 7. Total AGE Cart Allowance for 18 F-16s from COMPES

AGE Cart Name	Quantity	Weight (lbs.)	Volume (cu. ft.)	Area of Floor Space (sq. ft.)
Lighting	9	20520	2565	459.00
Power Generator	9	28080	2709	476.64
Cooling Air	9	12420	2763	479.25
Low-Pack Compressor	4	3280	508	148.22
Hydraulic Pressure	2	15500	948	144.00
High-Pack Compressor	1	1980	205	40.94
Liquid Nitrogen Cart	2	6800	482	105.00
Gaseous Nitrogen Cart	1	3400	241	52.50
TOTAL:	37	91980	10421	1905.54

These tables include *only the AGE carts themselves*. Additional airlift is

necessary to move the spare parts, tools, and personnel required to maintain these carts as

Figure 1 of Chapter I has already shown.

When these results are graphed, a clearer picture of how these seven AGE relate

to one another: the generator, light cart, and hydraulic cart comprise 69% of the weight;

the generator, air conditioner, and light cart comprise 77% of the volume; and the

generator, air compressor, and light cart comprise 73% of the floor space. It is no wonder that designs are being developed to integrate some of these functions into a single machine.
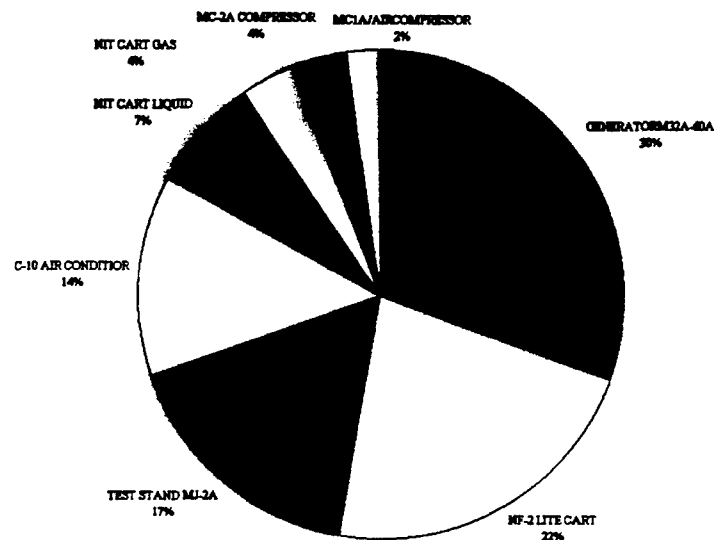
Figure 2. Total Weight Proportion for each AGE Type
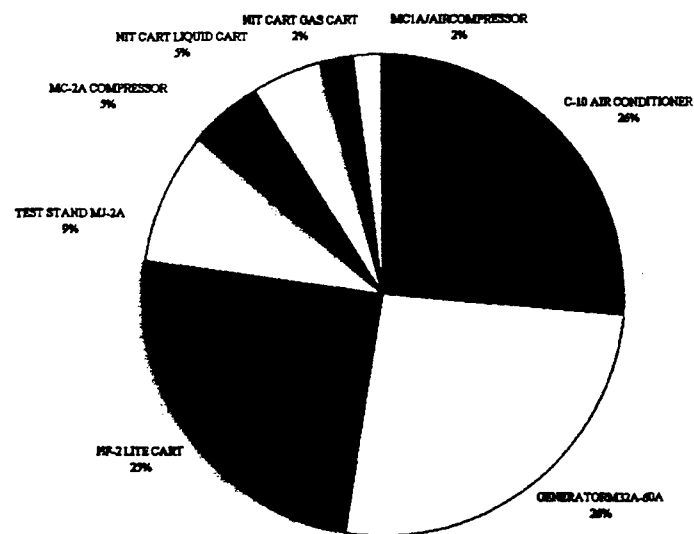
Figure 3. Total Volume Proportion for Each AGE Type
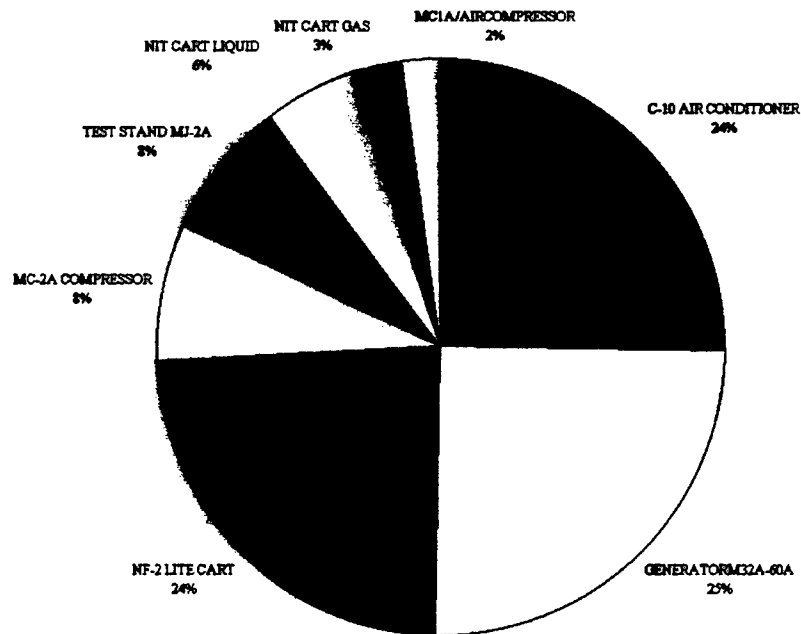
Figure 4. Total Floor Space Proportion for Each AGE Type

AGE Designs

Several alternate AGE package designs have been suggested. The first design

option is to keep producing the many different types of single function AGE carts.

Although using existing carts is relatively inexpensive, the deployability of fighter

squadrons would not be improved nor would the reliability or environmental impact of

AGE.

A second design would create a MASS cart that had the capability of only the two

most commonly used AGE carts—the generator and the air conditioner. This design is

being actively developed as the Combination Generator-Air Conditioner (CGAC). The

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prototype was originally referred to as the DASH 70 when Lockheed Sanders was commissioned to create a prototype. At that time, a specification was used in its development titled, DASH-ATSP-001 (Department of the Air Force, 1996c:3). This program is currently being managed by the Logistics Support Branch to the Generators Material Group at Sacramento Air Logistics Center, McClellan Air Force Base. A statement of objective has been written and coordinated. Allied Signal Aerospace was awarded the contract of prototyping and testing on 11 April 1997. Headquarters, Air Combat Command, Logistics Maintenance Branch has identified that the goal of this project is to evaluate a cart combining the attributes of the A/M32A-60A and A/M32C-10D into a single cart so that a reduction of strategic airlift/deployment footprint is observed in aircraft support equipment (Ansell, 1997:13). The size of this unit is estimated to be just a few inches taller and 250 pounds heavier that the existing -60 generator. All other AGE cart services would still need to be met by the traditional single function AGE carts (Assad, 1997).

The third design would be to reduce the number of AGE carts by introducing the Multifunction Aircraft Ground Support System (MAGSS) cart. These carts developed by Lear Astronics Corporation can perform several functions of single AGE carts using only a single multifunction cart. The MAGSS can replace the -60 Generator, the -10 Air Conditioner, the NF-2D light cart, the MC-2A low pressure compressor, the gaseous nitrogen cart, and the MJ-2A hydraulic servicing cart (It should be noted that the present lighting capacity of the MAGSS is half that of the NF-2D. The capability of the MAGSS to replace an NF-2D is still being determined by the users) (Witham, 1997). Reliability

estimates of the single existing prototype are better than the existing AGE carts which it would replace. The manufacturer specification for MAGSS identifies the goal MTBF of critical components (components necessary to produce the outputs of electricity, environmental air, pneumatic power, and hydraulic power) at 500 hours with a minimum acceptable value of 300 hours. The minimum acceptable value of MTBF of all other components is set at 150 hours (Developmental Sciences Center, 1995a:35). The MAGSS is specified as having an overall MTBF of 200 operating hours as its minimum acceptable value (Developmental Sciences Center, 1995a:33). The MAGSS MTTR was designed not to exceed 1.5 hours (Developmental Sciences Center, 1995a:34). One of the key concerns with this option is the high unit cost of each MAGSS.

A fourth and final design option considered in this thesis is combining usage of both the CGAC and MAGSS units in a single squadron's deployment package. This option is less expensive than the fully MAGSS package because only a few specialized MAGSS units need to be purchased while the remaining generator and air conditioning needs can be handled by CGAC units.

One option that is not analyzed in this thesis is the modular multifunction carts. Although no prototypes have been created, Battelle has done studies on the effectiveness of such a concept. The system would require several electrically wired flatbed carts and suitcase-like modules that would perform functions similar to existing AGE carts. These modules could be put on or taken off a flatbed cart at the discretion of the user. In this way, carts could be configured for the specific requirements of the maintenance job (Walters, 1996).

This research considers only the first four design alternatives. Although the modular MASS design offers promising capabilities, the feasibility of such a system is not yet demonstrated and limited information exists about such a system.

AGE Failure Rates

Previous AGE simulations primarily used a MTBF range of 100 hours and 10,000 hours for all AGE carts in the simulation (Carrico, 1996:23). However, recent AGE technician interviews indicate that different types of AGE do not have similar failure rates. MTBF can average near 900 hours for some AGE cart types and near 30 hours for others. In light of this information, a more appropriate range of MTBF values should be considered. Still, field interviews are not consistent. Consider Table 8 below that identifies three sources for MTBF and transcribes the manpower standards first reported in Tables 2 and 3 above.

Table 8. AGE Failure Reliability

| Cart | Model # | MTBF (operational hours) | | | MIL-STD # | Monthly Maintenance (hrs) |
		Hablanian	Hale	MIL-STD		
Hydraulic Test Stand	TTU-228E	300	4 to 20	152	MIL-T-38381B	51.23
Diesel Generator	AM32A-86D	500	20 to 111	N.A.		25.08
Gas Turbine Generator	AM32-60A	400	17 to 67	425	MIL-G-38195C	18.96
Air Cycle Cooling	AM32C-10C	2,300	20 to 116	435	MIL-A-83039B	4.89
High Pressure Air Compressor	MC-1A	700	26 to 50	500	MIL-C-26805G	10.08
Low Pressure Air Compressor	MC-2A	1,200	17 to 45	500	MIL-C-26805G	5.42
Liquid Nitrogen	A0411000	1,300	100 to 900	N. A.		15.41
Nitrogen Cart	NG-02	7,700	100 to 900	N. A.		3.42
Flood Light Cart	NF-2D	1,100	20 to 173	N. A.		13.86

Source: Hablanian, et al, 1997; Hale, 1996:18-19; Department of the Air Force, 1996[2]:17-18

No easy answer exists as to why there are large differences in the reported MTBF. It has been mentioned that the estimates provided by Hablanian (1997) are more closely characterized as theoretical maximums to the reliability of the machines (Tracy, 1997).

However, I will postulate that the unusually low reliability reported by the Hale study is due to collecting data from peacetime bases with peacetime levels of activity. As such, AGE may remain inactive for longer periods than during high wartime levels. When conditions finally do require the usage of the cart, the cart has been sitting so long that failures due to inactivity have occurred (e.g., flat tire). Such a theory would suggest that modeling AGE failure based on operational hours is not wise. However, AGE is bound to be used more often during a military operation, so the failure rate in terms of operational hours may decrease.

Although differences do exist in the estimates, trends are apparent. For example, the hydraulic test stand has the lowest MTBF value in each of the three sources and it has the highest expectation of monthly service hours. The nitrogen cart has the highest MTBF value in each of two sources and it has the lowest expectation of monthly service hours. As such, a pattern emerges that some carts are much more reliable than others.

This pattern is contrary to the modeling assumptions made by Carrico (1996), Zahn (1995), and Walters (1996). In Carrico and Zahn, a lognormal distribution was used with a MTBF of all AGE types set at two different values: 100 hours and 10,000 hours. The variance was set at five hours when MTBF was 100 and was set at zero hours when MTBF was 10,000. The authors concluded that only a weak correlation existed between aircraft PCMs and the failure rates of AGE (Carrico, 1996:12-13,22-23). In the report by Walters, the MTBF was set at 1000 hours (Walters, 1996:A-20). These previous studies were performed before most of the information in Table 8 was published.

AGE Repair Rates

Minimal data exists on the mean time to repair (MTTR) the AGE carts. Carrico

and Zahn used a MTTR of five hours while Walters used two hours. However, each of

these values was based on minimal field experience. Hale (1996:18-19) reported MTTR

estimates from AGE personnel at five bases just as he reported MTBF values (see Table 8

for his MTBFs). The estimates for MTTR identified in that report are listed in Table 9.

Table 9. Mean Time To Repair (MTTR) Estimates

AGE Cart Name	Model #	MTTR (hours)
Hydraulic Test Stand	TTU-228E	1 to 5
Gas Turbine Generator	AM32-60A	0.75 to 5
Air Cycle Cooling	AM32C-10C	1.2 to 5
High Pressure Air Compressor	MC-1A	0.5 to 8
Low Pressure Air Compressor	MC-2A	0.5 to 2
Liquid Nitrogen	A0411000	0.5 to 4
Nitrogen Cart	NG-02	1 to 4
Flood Light Cart	NF-2D	2 to 4

Source: Hale, 1996:18-19

AGE Deployment Footprint

Tables 4 and 5 include the dimensions and weight of each traditional AGE cart.

The dimensions and weight of the developmental MAGSS and CGAC units are identified

in Table 10 below.

Table 10 Deployment Footprint of Future AGE Carts

AGE Cart Name	Weight (lbs.)	Length (in.)	Width (in.)	Height (in.)	Volume (cu. ft.)	Area of Floor Space (sq. ft.)
CGAC	3370	120	68	68	321.11	56.67
MAGSS	6500	130	67.5	74.2	376.80	60.94

Source: Assad, 1997a; Developmental Science Center, undated:2

The deployment footprint of AGE carts is certainly not just the sum of all the individual AGE carts. These carts also require spare parts, tools, manuals, fuel, and mechanics to keep them in working order. None of the weights of the actual carts include such items. As an example, 19 AGE maintenance personnel are deployed to support an independent 18 aircraft F-16C/D squadron (Gaumer, 1996:11). Unfortunately, documentation of which spares and tools are deployed in sole support of AGE is unavailable. Such information could become available with different UTC reporting methods.

Another key point to appreciate when considering the deployment footprint of the AGE carts is how the AGE cart design influences the number of airlift missions necessary to relocate the equipment to the new operating base. Typically, the cargo of an airlifter reaches maximum floor space capacity on the aircraft before it exceeds the maximum cargo weight restriction (Gaumer, 1996:30). As such, identifying how many aircraft are required to fit the cargo on the floor is typically the best method to determine the deployment impact of the equipment. The Computer Aided Load Manifesting (CALM) model is the AF developed model used to automate load planning the process of airlift (Gaumer, 1996:46). A disadvantage of this method is that it requires the assistance of a qualified load planner to manipulate CALM and determine the number of airlift aircraft needed to move the cargo. When a certified load planner is unavailable, a rough estimate of the number of aircraft necessary for deployment can still be developed using an expected value of 5200 cubic feet of cargo space for each C-141 used (Aeronautical Systems Center, 1993:7).

AGE Costs

The costs associated with AGE are not trivial to identify. A complete analysis of AGE costs would include all life cycle costs including, but not limited to, the costs to develop, procure, maintain, and dispose of the AGE. The treatment of AGE costs in this thesis are far more simplistic. The unit cost of each AGE cart used for this thesis are identified in Table 11.

Table 11. AGE Cart Costs

AGE Cart Type	Unit Cost (FY93$)
Flood Light	$ 10,000.00
Gas Turbine Generator	$ 40,000.00
Air Cycle Cooling	$ 57,000.00
Low Pressure Air Compressor	$ 7,900.00
Hydraulic Test Stand	$ 40,000.00
High Pressure Air Compressor	$ 21,000.00
Liquid Nitrogen	$ 28,000.00
Gaseous Nitrogen	$ 28,000.00
MAGSS	$ 390,000.00
CGAC	$ 150,000.00

Source: ASC, 1993:34 (except CGAC cost)

CGAC unit costs were unavailable from the Program Manager (Assad, 1997b). As such, the cost of each CGAC in this report is estimated to be the combined cost of a -60 generator and a -10 air conditioner plus approximately 50%. The additional 50% is added to the estimate to account for allocating the fixed cost of designing the CGAC since the individual cost of designing the generator and air conditioner have long since been allocated. Better estimates will no doubt be available as the program matures.

The total cost for the AGE hardware can be contrasted against the cost of airlift. The cost of airlift during a deployment can be determined by multiplying the cost per flying hour by the number of sorties by the sortie duration in hours. The cost per flying

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hour in FY 1993 was $3,150. This cost includes all the direct costs of flying a C-141 including fuel, depot maintenance, depot level repairable, base maintenance supplies, and crew per-diem costs. As an example, it takes an average of 12.7 hours to fly from Mountain Home AFB, Idaho to Cairo West, Egypt. So, the direct cost of a single sortie is $40,005 (Aeronautical Systems Center, 1993:34). Note that the direct costs are only part of the total costs of the mission since it does not include the indirect costs of pilot training, pilot salaries, management and infrastructure of the airlift base.

Logistics Modeling

Introduction

Many models have been built to address questions surrounding the operation of an air base. Numerous models have even been used to understand how logistics affects aircraft availability. Forty-six base-level logistics models were identified and classified in 1971 (Paulson, 1971:50). Of these, 19 had applications in AGE (Paulson, 1971:50). Certainly, there are no less today. In fact, over 7,800 logistics-related models are maintained by the Defense Logistics Studies Information Exchange (DLSIE, 1995:5). Although only a small portion of these models relate in scope to the daily activities of an air base, numerous models do abound.

Logistics Composite Model (LCOM)

One of these models that has maintained a high degree of use for several decades is the Logistics Composite Model (LCOM). LCOM was created by the Rand Corporation under contract with the Headquarters, Air Force Logistics Command, in the

1960's. The goal of the project was to create a model that would assist decision makers in testing and evaluating the evolving repair and maintenance policies at a tactical air base. It was envisioned that such a model would help leadership determine the best mix of personnel, ground support equipment, repair parts, transportation, communications and other supporting resources to satisfy base and depot level repair (Fisher, 1968:2-3). The model was developed using information obtained from an operational test of F-4Cs in the first six months of 1967 (Fisher, 1968:2-3).

Besides the initial collection of information in 1967, LCOM has been revised and revalidated on several occasions. The most elaborate validation of LCOM was performed by Headquarters, Tactical Air Command, in the 1970s using F-4Es. Three different levels of validation were performed. The first was a rough validation. In this stage, simulated manpower results were compared to known requirements at an aggregate level. The LCOM results were similar to reality. This stage was considered rough, however, because comparisons were performed across all maintenance work centers and not by individual work center. The second phase of validation was a "good" validity check. In this phase, simulation output measurements were compared to the actual measurements collected from three different bases. Again, favorable results were found. The final phase was identified as "proof positive" validation step. In this phase, LCOM was used to determine the required manpower and logistics resources to maintain and fly a realistic flying schedule. Headquarters, Tactical Air Command, then provided the same size unit as LCOM predicted and flew a realistic schedule using the same rules that were in effect for LCOM. The unit was able to fly the schedule satisfactorily as LCOM predicted.

These three phases were developed to test the prediction capability of LCOM and the model's ability to duplicate performance measures of a flying squadron (Department of the Air Force, 1973:Section 1 Page 6-Section 1 Page 8). It is unclear whether any further validation studies have been performed that match the magnitude of that project. However, over 25 AFIT theses have been devoted to LCOM's study and improvement (Cronk, 1997b). Additionally, numerous LCOM studies by other contractors and military agencies have been performed throughout the years.

In 1981, LCOM became a standard Air Force automated data processing system (ADPS) and was identified as ADPS-14 (Derenzo & Theis, 1983:8). Models have been developed for many military systems including aircraft carrier flight and maintenance operations, SH-2d anti-submarine warfare helicopter, the F-18 and A-12 aircraft, and the recently procured C-17 airlifter (Cronk, 1997b). The model is maintained by the Air Force Center for Quality Management Institute (AFCQMI) and the Aeronautical Systems Center (ASC) (Boyle, 1990:1). Also, Headquarters, Air Combat Command (ACC), maintains an office devoted to LCOM's application (Cronk, 1997b). In fact, a simulation and analysis representative from Headquarters, ACC, stated,

> *LCOM is our most frequently used simulation model and is used as the tool of choice to determine air maintenance manpower requirements for all ACC weapon systems. . .However, LCOM is by no means limited to the development of maintenance manpower requirements. . . Logistics resources modeled in LCOM include not only manpower but spare parts, support equipment, and facilities. Hence, the value of LCOM as an analysis too for ACC is boundless. The Simulation and Analysis Staff (XPMEL) at ACC work numerous special projects for the Logistics (LG), Operations (DO), Requirements (DR), and Plans and Programs (XP) Directorates.* (Schneider, 1996:7)

The model has been successfully used to predict the supportability performance of fighters, bombers, tankers, and trainer aircraft. Although the model was used primarily to justify maintenance manpower authorizations for annual AF budgets in the past, the model is being used for the majority of F-22 and JSF logistics modeling needs (Wallace, 1997). The JSF usage of LCOM is especially important because it transcends LCOM from an AF-specific model to a multi-service, multi-national tool (Wallace, 1997). The model can be used to analyze seven of the ten Integrated Logistics Support (ILS) elements (Cronk, 1997b). Those elements are:

1. Maintenance Planning

2. Manpower and Personnel

3. Supply Support

4. Support Equipment

5. Facilities

6. Design Interface

7. Packaging and Handling

LCOM has become a cornerstone of the Air Force modeling culture with an entire Air Force manual and regulation written about its proper application (Department of the Air Force, 1992; Department of the Air Force, 1987).

Presently, LCOM is updated monthly by data that is transferred from maintenance automated collection systems such as Core Automated Maintenance System (CAMS) and Reliability Maintainability Information System (REMIS) (Cronk, 1997a). LCOM is not

so much a single simulation any more as it is a data warehouse of information critical to simulation construction. Although LCOM is constantly being modernized, the legacy nature of LCOM has led the LCOM Steering Committee to vote to transfer the information of LCOM into an object oriented programming language (Brown, 1997). One such language being considered is the Integrated Model Development Environment (IMDE) developed by Armstrong Laboratory.

Integrated Model Development Environment (IMDE)

IMDE is a computer aided software engineering (CASE) tool that offers the benefits of object oriented programming and graphical user interface. Object oriented programming (OOP) provides several benefits over traditional programming. OOP allows for the creation of reusable objects in the development of simulation programming. As such, a reduction in overall programming code is achieved. In this way, model building analysts can grab many previously developed objects and tailor their characteristics to suit the present modeling requirements. IMDE can then take all the defined objects and generate an executable model using only the objects selected by the model developer. In this way, a model developer can selectively add or subtract procedures from an extremely large logistics model such as LCOM to suit the needs of the decision maker (Zahn, 1995:1195-1197; Lloyd, 1994:131-133).

MASS Model

One of the initial applications of IMDE was in the development of a model to study the implications of the new MASS cart. Carrico (1996) and Zahn (1995) used IMDE to develop a simulation that predicted the utilization rate of different AGE

components and the PCM of aircraft. Although the processes used for modeling aircraft failure were established prior to this study, the processes used for modeling AGE utilization and failure were not. Interviews with AGE mechanics at Springfield Air National Guard, Ohio, helped determine what types of AGE would be needed for the 614 different failures that could occur on the F-16. It was then decided that one piece of AGE would be required to be physically located and operating at that aircraft for the duration of the repair process. It was also decided that no AGE would be required for an aircraft that returned to base with no failures (Carrico, 1996:14).

Carrico (1996) identified electrical and air conditioning as the most critical service because of the high demand observed. They also concluded that eight all-in-one MASS units were adequate to support 18 F-16 aircraft during a 2.0 sortie schedule. The utilization rate of the MASS units was found to be similar to that of a generator (Carrico, 1996:1). Several factors were also investigated by varying a single factor at a time and observing the effects on PCM and AGE utilization. The factors MTTF and MTTR were found to cause statistically insignificant differences in the PCM when allowing one or the other to fluctuate (Carrico, 1996:22-25). However, the interaction between the two was apparently not investigated. The number of repair staff was also found to lack statistical significance when varied individually. Travel time and schedule type, however, were found to strongly affect PCM (Carrico, 1996:21).

Since the time of that simulation study, another simulation study was performed by Battelle (Walters, 1996). That study addressed an area not covered by the MASS IMDE study—modularity. A model was built where the MASS carts were dynamic in

that the AGE repair shop could add or subtract any or all of the seven AGE cart functions

to a single cart. Unfortunately, the designers did not desire the complexity of modeling

the F-16 using the 614 failure modes (four digit WUCs) of the previous study. They

chose to model a mere 50 failure modes (aggregation to a two digit WUC) instead.

Although the creativity in tackling the issue of modularity is commendable, the lack of

detail in modeling the failures of the F-16 in a manner consistent with the LCOM and the

maintenance data available raises questions about the reliability of their results

(especially since these processes were already accredited by the AF). The results of the

Battelle study are not reported because the aircraft modeling techniques used were too

limited in scope from the viewpoint of this thesis.

Analytic Models

The complexity of resources and processes used to sustain aircraft sortie

generation has precluded the use of analytical models for all but the most crude analysis.

Simulation, it seemed, offered an almost limitless capacity for detail and complexity

within a model while still offering an answer to the study's questions. However, the

answers presented by simulation are strongly influenced by the pseudo-random numbers

used during the execution of the program. Even assuming perfectly random numbers, the

solution of the simulation would be a mere point estimate of the true value. Therefore,

the search for analytical models that provide objective solutions to question arising from

a logistics environment is still actively pursued. A recent paper on the "Analysis of

Aircraft Sortie Generation with the Use of a Fork-Join Queuing Network Model"

confirms that the gap between complex analytic and simulation logistics models is

narrowing (Dietz, 1997:1). Soon analytic models should be available to—at the very least—bound the solutions of detailed logistics simulations and—at best—replace much of logistics modeling with precise answers that are consistent with the assumptions of the logistics scenario. Although some may be threatened by such mathematically-intensive approaches, the future of logistics as a science relies on such efforts. Although this paper primarily uses simulation to model the complexities of a process with constrained resources, future analysts should focus on new opportunities to use analytical models for logistics research.

Although modeling the operational effects of AGE is not conducive to analytic modeling, other aspects of AGE modeling are not so restricted. In the following chapters analytical modeling will be used to determine the total cost of an AGE cart package and to determine deployment footprint of the AGE carts.

Summary

Logistics modeling has a rich heritage and a bright future. Logistics resource modeling has shared a similar history. Such models have always and continue to address utilization of ground support equipment such as AGE. However, the results of these AGE models were viewed only by the model designers and a few low-level decision makers until recently. The lack of attention may be due to the perception that AGE is to be pre-positioned and to be purchased using existing designs. However, the reduction of overseas assets and the increased attention given to expensive overseas deployments requires new analysis and decisions about how AGE supports bombs-on-target.

Several recent reports on modeling AGE and the operational characteristics of AGE were identified. None of the reports used present reliability estimates of AGE carts in their analysis. None of the reports used Analysis of Variance (ANOVA) techniques to identify factors that cause statistically significant differences in aircraft PCM. Past reports only minimally reported the costs and deployment footprint of present and future AGE package options. In the next chapter, a methodology is developed to improve and integrate the previous research into a more complete picture of AGE's impact by identifying AGE-related factors that still require better estimates before operational results can be estimated and by analyzing the costs and deployment footprint of a few AGE package options of the future.

III. METHODS

Introduction

This chapter discusses the methodology used in the research process to answer the research questions identified in Chapter I. The research questions are reviewed and expectations are identified. Then the general research design is explained. Finally, the method of implementing the research design is presented in five phases.

Research Questions and Expectations

Using present range estimates as levels for our factors, do statistically and practically significant differences in the expected PCMs exist?

My prediction was that all of the factors being analyzed will be statistically significant. This would demonstrate that the estimated range is still too wide to examine the true operational capabilities of each design alternative.

What is the deployment footprint for each AGE design option?

My prediction was that the newer MAGSS and CGAC options would reduce the deployment footprint of AGE carts.

What are the costs involved with each alternative?

My prediction was that the traditional AGE option would be the least expensive alternative, but that the other options would be close in price.

Which options are efficient in overall value?

My prediction was that the newer options will be more expensive but will also reduce the deployment footprint. As such, each of the options will be efficient in terms of cost vs. deployment tradeoffs.

Research Design

The method used to answer the research questions has five phases. The first phase was to utilize a simulation model to generate the estimated operational effectiveness of each treatment. The second phase was to identify which factors are statistically significant. The third phase was to calculate the airlift requirements for each treatment. The fourth phase was to calculate the costs of each treatment. The final phase was to evaluate each treatment in terms of both its operational and deployment profile.

Phase I. Estimate Aircraft Availability of Each Treatment Using a Simulation Model

Phase Ia. Simulation Model

The MASS simulation model used by Carrico (1996) and Zahn (1995) was used to obtain estimated values for the PCMs. This is the simulation that was written in IMDE and primarily used LCOM procedures to provide the estimates for aircraft availability. PCM was used as an operational definition of overall operational effectiveness of the maintenance system (which includes support equipment). The higher the PCM, the lower the operational effectiveness of the maintenance system. Simulation variables were set as either constant across all alternatives or set to vary according to each scenario.

Phase Ib. Identify the Common Configuration/Assumptions

Many items of the simulations were treated consistently throughout the entire experiment:

1. Calibration/Verification/Validation

2. Aircraft Squadron

3. Aircraft Failure/Repair Modeling

4. AGE Usage

5. Model Duration

6. Replications

7. Model Logic

Calibration/Verification/Validation

The MASS simulation code developed by Carrico and Zahn using IMDE was last used over two years ago. Although the program was extensively verified at the time of the last simulation studies, there was some concern that files may have been corrupted inadvertently. Therefore, before any experiments were run for this study, a test of the model was performed to ensure that the published results of the Carrico study still matched those determined by the present software. Experiment 42 of Carrico (1996:38) was used. The resulting 30 PCM values were tested against the mean and sample variance reported by Carrico (1996). The null hypothesis was that the true means of each treatment were the same. The alternate hypothesis was that the true means of each treatment were not the same. To test whether the difference between the two means is statistically significant, a Confidence Interval (CI) of the difference between two

population means was used. A 95% CI of the difference was used. If the CI included zero, insufficient evidence would exist to conclude that the two were different. If the CI did not include zero within its range, then the conclusion that a statistically significant difference does exist between the results reported by Carrico and the results reported in this thesis. Since the sample size of each treatment was large, the hypotheses were tested by creating a confidence interval of the true difference between the means by using the following formula (Devore, 1995:354):

$$xbar - ybar \pm z_{\alpha/2} \sqrt{\frac{s_1^2}{m} + \frac{s_2^2}{n}}$$

Where:

$xbar$ = the mean of PCM in this study

$ybar$ = the mean of PCM in Carrico's study

$z_{\alpha/2}$ = the z-statistic score at the $\alpha/2$ level

s_1^2 = the sample variance of PCM in this study

s_2^2 = the sample variance of PCM in Carrico's study

m = the sample size of this study

n = the sample size of Carrico's study

The decision rule is that if the confidence interval created in the formula above does not include zero, then the null hypothesis is rejected. The significance level of the test used was set at $\alpha = 0.05$. Since both samples sizes are 30, both samples can be sufficiently characterized as large. The results of this test are provided in the next chapter.

Since all of the processes used by the model had already been validated during previous research (in fact research spanning several decades), little original validation efforts were performed. Just as the parameter estimates of AGE failure rates have been modified from previous AGE modeling efforts to match present theory, so too should the results of this study be modified to consider new information as it becomes available (see AGE Usage/Failure/Repair Modeling section below for a more detailed account).

Aircraft Squadron

A single squadron of eighteen F-16 aircraft was modeled. A daily schedule that included 36 sorties per day was used. Mission duration was normally distributed with a mean of 1.8 hours and a variance of 0.5 hours. The flying schedule used was the same as schedule 18b used by Carrico (1996:92):

- 10 aircraft sorties launched in pairs at 0600

- 10 aircraft sorties launched in pairs at 1200

- 10 aircraft sorties launched in pairs at 1800

- 6 aircraft sorties launched in pairs at 2200

Eighteen aircraft is a typical squadron deployment size. Two sorties per day flown predominantly during daytime environment is typical of a *rigorous* sortie schedule with reasonable separation in generation cells.

Before the scheduled launch time, the simulation is programmed to identify aircraft available to fly the missions. Theoretically, the same aircraft could fly in each of the four launching periods while another aircraft might sit out the entire day being repaired. Aircraft were launched in pairs. If the number of available aircraft was less

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than the total needed, only an even number of aircraft were sent. This occasionally left a single available aircraft grounded while operational missions went unfulfilled.

Aircraft Failure/Repair Modeling

All processes concerning the failure rates of F-16s and their repair times were taken directly from the LCOM database. Over 614 different unscheduled maintenance tasks or work unit codes (WUCs) are modeled (Zahn, 1995:1194) from a database developed from over 80,000 F-16 flying hours (Longstreth, 1997: 2). The simulation has been established to use the best-fitting exponential distribution for time between failures and the best-fitting lognormal distribution for repair times.

Manpower and Spare Parts

The MASS simulation is sophisticated enough to model manpower and spare parts. The quantity of personnel with training in each specialty related to aircraft and AGE maintenance can be modeled as a resource. The resource pool can be incremented and decremented as the personnel are called to repair aircraft or AGE. In fact, specific manpower quantities and training requirements can be identified for the repair of each F-16 failure mode. Perhaps some jobs require two senior avionics maintainers while others require a single junior hydraulics maintainer. Likewise, the number of spare parts available to replace failed line replaceable items can be specified.

For this thesis, the number of spare parts and the amount of manpower was unconstrained. Certainly, future studies could more tightly limit access to these resources.

AGE Usage

LCOM does not contain detailed information of the usage of AGE carts. A matrix was developed by Carrico (1996) that identified the types of AGE carts necessary to complete each aircraft repair. The matrix was developed through interviews with the AGE maintenance staff at the Springfield Air National Guard Base, Ohio (Carrico, 1996:9). An exhaustive reproduction of the four digit WUCs and the necessary AGE and personnel required for each job is available (Carrico, 1996:39-91). The reader interested in a follow-on study using similar methodology to this thesis is strongly urged to review the study by Carrico (1996) for details regarding this matrix.

Model Duration

The simulation was run for a 30-day deployment which is the same as the method used by Carrico (1996:14) and Zahn (1995:1196). The initial 30 days of a deployment is often called the surge period. After 30 days, the sustainment period begins. This thesis models only the surge period. However, a simple alteration to the input files of the simulation could be made to study PCM across a longer period.

Replications

Fifteen replications were run of each treatment so that the stochastic nature of the simulation output could be better understood. With 15 estimates of PCM, normality, constancy of variance, and independence were tested and a treatment mean was calculated.

Model Logic

The simulation sought an operational aircraft until one was found or until the cancel time of 30 minutes after the scheduled mission takeoff. A sortie was considered aborted if no operational aircraft was found during this time.

An AGE cart was considered as being utilized and removed from the resource pool from the point in time when it was assigned to an aircraft until the unit was returned to the AGE shop. The utilization includes any travel time to and from the AGE shop.

Each simulated cancellation of a scheduled mission was recorded at the time of the abort as was the total number of successful missions. The number of canceled missions was divided by the total number of aborted and completed missions to get an overall PCM. PCM is used as the definition of aircraft availability.

Phase Ic. Identify the Differences Between Treatments

Several different levels of the factors identified in Chapter I were modeled. The goal was to see which combinations caused significantly different PCMs. Scenarios were selected for several reasons. First, three different MASS designs were tested against each other and against a more traditional AGE package. Second, the influence of travel delay on moving the AGE carts around the flightline was considered. This travel delay could be caused by any or all of the following factors: widely-spaced flightline, limited tugs to move carts, or communication delays of the movement order. The exact reason for the delay is insignificant to the research. The fact that the delay exists is the only concern. Third, the MTBF of AGE carts was varied. Finally, the MTTR of AGE carts was varied.

AGE Service Capability

The following alternative AGE designs were considered:

1. Current Status Quo AGE package

2. Integrating the Combined Generator/ Air Conditioner (CGAC)

    into the AGE package

3. Integrating Multifunction Aircraft Ground Support System

    (MAGSS) into the AGE package

4. Integrating both the CGAC and MAGSS into the AGE package

Each of these four designs was considered as a potential deployment package

configuration of the future. The analysis in the next chapter will determine whether the

differences in design caused statistically significant differences in PCM.

AGE Failure/Repair Modeling

As explained in Chapter II, limited data exists about frequency of AGE cart

failure or the duration of their subsequent repair. Apparently, the testing data used when

initially fielding these systems has been lost to the AGE community in the decades since

many of these units were designed, if in fact these units ever underwent classical failure

and repair testing.

However, new information like that identified in Chapter II has started to appear.

For existing AGE carts, this thesis used the low estimate of MTBF and twice the high

estimate of MTBF according to the information published by Hale (1996:18-19) because

this is the only report that actually interviewed AGE mechanics in the field. The

doubling of the high estimate was used to compensate for much higher theoretical

estimates reported by Hablanian, et al (1997). Likewise, this thesis will use the Hale report (1996:18-19) to set MTTR at the levels of one hour and five hours. These two values seem to encompass the approximate range published by Hale (1996:18-19) and the ranges used by Carrico (1996), Zahn (1995), and Walters (1996).

The Hale report (1996:18-19) provides failure repair data for all AGE carts except the MJ-2A, CGAC, and MAGSS. This thesis uses the data supplied for the TTU-228 to model the data needed for the MJ-2A. Both AGE carts are primarily hydraulic carts and this thesis assumed that the MJ-2A has similar maintenance characteristics as the notoriously poor TTU-228. The MTBF and MTTR used for the MAGSS were developed by considering the specifications identified by the manufacturer, Lear Astronics, as identified in Chapter II. The levels used in this thesis used 150 hours and 500 hours for the high and low treatments of MTBF. One and five hour MTTR treatment levels were used. These MTTRs bracket the manufacturer's specification of a MTTR of 1.5 hours. The MTBF and MTTR used for the CGAC were estimated by reasoning that the CGAC should have a reliability at least as high as the MAGSS since the CGAC is being designed after the MAGSS and the CGAC is far less complex than the MAGSS.

Travel Time

The amount of time it takes an AGE cart to travel around the flightline was examined. The delay was modeled as a constant and was applied whenever an AGE cart was moved from aircraft to aircraft or from/to the AGE shop. Two treatment levels were used: 15 minutes and 45 minutes. The delay was not applied when the same aircraft required the AGE cart for two sequential jobs.

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Type and Number of AGE

The type and number of AGE carts used in the study are based upon the information in Table 6 and rely heavily on the source identified for that table. Tables 12, 13, 14 and 15 identify the parameters used when simulating traditional, CGAC, MAGSS, and CGAC/MAGSS AGE packages.

Table 12. Traditional AGE Quantities Used

Name	Tech Name	Quantity	MTBF Low	MTBF High	MTTR Low	MTTR High
High-Pack Compressor	MC-1A	1	26	100	1	5
Low-Pack Compressor	MC-2A	4	17	90	1	5
Liquid Nitrogen Cart	N2 Cart	2	100	1800	1	5
Gaseous Nitrogen Cart		1	100	1800	1	5
Cooling Air	AM32C-10	9	20	232	1	5
Power Generator	AM32A-60	10	17	134	1	5
Hydraulic Pressure	MJ-2A	2	4	40	1	5
Lighting	NF2D	9	20	346	1	5

Table 13. Combined Generator/Air Conditioner AGE Package Size Used

Name	Tech Name	Quantity	MTBF Low	MTBF High	MTTR Low	MTTR High
Comb. Gen / AC	Dash 70	6	150	500	1	5
High-Pack Compressor	MC-1A	1	26	100	1	5
Low-Pack Compressor	MC-2A	4	17	90	1	5
Liquid Nitrogen Cart	N2 Cart	1	100	1800	1	5
Gaseous Nitrogen Cart		1	100	1800	1	5
Hydraulic Pressure	MJ-2A	2	4	40	1	5
Lighting	NF2D	9	20	346	1	5

Table 14. MAGSS Configuration AGE Package Used

Name	Tech Name	Quantity	MTBF Low	MTBF High	MTTR Low	MTTR High
MAGSS		6	150	500	1	5
High-Pack Compressor	MC-1A	1	26	100	1	5
Liquid Nitrogen Cart	N2 Cart	2	100	1800	1	5
Lighting	NF2D	3	20	346	1	5

Table 15. MAGSS & CGAC Combination AGE Package Used

Name	Tech Name	Quantity	MTBF Low	MTBF High	MTTR Low	MTTR High
MAGSS		2	150	500	1	5
Comb. Gen / AC	Dash 70	4	150	500	1	5
High-Pack Compressor	MC-1A	1	26	100	1	5
Liquid Nitrogen Cart	N2 Cart	2	100	1800	1	5
Lighting	NF2D	7	20	346	1	5

Table 16 identifies the treatments that were simulated in order to estimate the effects that the factor estimates have on PCM.

Table 16. Experimental Design

Treatment #	AGE TYPES	MTBF (operating hrs)	MTTR (hrs)	Travel Time (min)
1	Traditional	Low	1	15
2	Traditional	Low	1	45
3	Traditional	Low	5	15
4	Traditional	Low	5	45
5	Traditional	High	1	15
6	Traditional	High	1	45
7	Traditional	High	5	15
8	Traditional	High	5	45
9	CGAC	Low	1	15
10	CGAC	Low	1	45
11	CGAC	Low	5	15
12	CGAC	Low	5	45
13	CGAC	High	1	15
14	CGAC	High	1	45
15	CGAC	High	5	15
16	CGAC	High	5	45
17	MAGSS	Low	1	15
18	MAGSS	Low	1	45
19	MAGSS	Low	5	15
20	MAGSS	Low	5	45
21	MAGSS	High	1	15
22	MAGSS	High	1	45
23	MAGSS	High	5	15
24	MAGSS	High	5	45
25	MAGSS & CGAC	Low	1	15
26	MAGSS& CGAC	Low	1	45
27	MAGSS& CGAC	Low	5	15
28	MAGSS& CGAC	Low	5	45
29	MAGSS& CGAC	High	1	15
30	MAGSS& CGAC	High	1	45
31	MAGSS& CGAC	High	5	15
32	MAGSS& CGAC	High	5	45

Phase Id. Identify the Collection Method used for Obtaining Results

The MASS simulation used to estimate PCM was run on a Sun SPARC 20 workstation with a SOLARIS operating system. An output file was created for each replication of each treatment listing the number of aborted sorties in the 30 day period. A script was used to aggregate these values into a single file sorted by treatment. This aggregated file was moved from the Sun SPARC 20 system to a personal computer running Windows 95 operating system using a File Transfer Protocol (FTP) software application. The data file was converted into a Microsoft EXCEL spreadsheet. Then the data was converted from a Microsoft EXCEL format into a STATISTIX format. STATISTIX is a product of Analytical Software. All statistical analysis was done in STATISTIX using the built-in subroutines of the STATISTIX application.

Phase II. Identify which factors are statistically significant

Fixed effect, single response, four factor, Analysis of Variance (ANOVA) techniques were used to determine which factors have statistically-significant differences in PCM estimates. The four factors identified in Table 16 were used at the designated treatment levels. Each treatment was replicated 15 times. All main effects and interactions were included in the ANOVA analysis. A Type I error level of $\alpha=0.05$ was used to determine significant effects.

Included in the analysis is a validation of the assumptions necessary for the application of ANOVA. Namely, that the residuals created by subtracting each treatment

mean from each replication value are, normally distributed, share a common variance between all treatments, and are independent.

This thesis tested the normality assumption by plotting the ordered residuals of each treatment against z-statistic rankits on a normality plot and observing whether they fall on a straight line. A straight line indicated that the residuals appear normally distributed. The Wilks-Shapiro statistic value for each treatment is used to test normality. The Wilks-Shapiro Test can be viewed as being approximately equal to the coefficient of correlation between the ordered residuals and their expected values (Neter, 1996:110). Since this thesis tested 32 treatments simultaneously, the α level needed to be allocated across all 32 tests in a manner similar to Bonferroni inequalities (Devore, 1995:505). Therefore, if a joint confidence coefficient of 1-α% is desired, each individual test must be performed at an $\alpha/32$ level of significance. A level of significance of $\alpha/32 = 0.005$ produces a family confidence level of 84%. The critical value for the coefficient of correlation test for normality with $\alpha/32 = 0.005$ is 0.895 (Neter, 1996:1348).

This study tested the common variance assumption of the residuals by using a couple different statistical tests. The residuals are plotted against the treatment means. If the residuals display a pattern of increasing or decreasing their spread from zero as the treatment mean increases, then the common variance assumption is suspect. A Bartlett's Test of equal variance using the Chi-Squared distribution was also used. With the test, a P-value is computed based on the Chi-Squared distribution.

Since a simulation was used to generate the PCM results, independence of each replication is a reasonable assumption as long as the stochastic events in the simulation

are modeled using a competent random number generator. Because the simulation model begins each treatment using the same seed for the random number stream, it is possible that the first replication of each treatment (and subsequent replications) may be influenced similarly in the generation of the PCM value (i.e., an induced correlation). To test this theory, two procedures were performed. First, the residuals are graphed against their replications number. If the residuals display some sort of pattern or if they increase or decrease their absolute distance from zero as the replication number increases, then there is cause for concern. Second, a new factor, replication number, was added into the ANOVA model. This factor was used as a blocking variable. Since it is assumed that the replication number would have no relationship to any of the other variables, no interactions with replication number were considered. The portion of the sum of the squared error (SSE) that is attributable to this factor was removed from SSE. Thus, the sensitivity of the ANOVA test was improved because the probability of missing a statistically significant factor or interaction was reduced. This research was not too concerned about erroneously identifying a factor as statistically significant because our recommendation for such situations is to perform more field studies on AGE carts. Extra effort in this area is not necessarily undesirable. However, claiming a factor as being statistically insignificant carries the recommendation to cease field studies on that variable and begin trade-off analysis. Such analysis would be flawed. This study would rather identify a factor or interaction as significant than identify that factor to be insignificant.

Phase III. Calculate the Airlift Requirements for Each Treatment

The dimensions of the traditional AGE were developed using information

available in Zahn (1995:1195) and the force modules of an F-16 LANTIRN aircraft from

COMPES LOGMOD-B (Griffis, et al, 1997). Where the two studies differed, the data

from COMPES was used. The dimensions of the CGAC were developed using the

interview with the CGAC Program Manager, Ms. Vicki Assad (1997a). The dimensions

of the MAGSS unit came from pamphlets by the manufacturer, Lear Astronics

(Developmental Sciences Center, undated:2).

The total space required for an entire deployment package of AGE was developed

by multiplying the number of each type AGE carts used in the deployment package

configurations by the cubic feet, pounds., or square feet of each AGE type and then

summing the total.

No certified load planner was available to determine how many aircraft would be

required to move the total AGE carts using CALM. As such, this thesis used a rough

estimation technique developed by Northrop (Aeronautical Systems Center, 1993:7)

whereby a C-141 was said to be capable of carrying 5200 cubic feet of cargo in a single

load.

Phase IV. Calculate the Costs of Each Treatment

The acquisition cost of an entire AGE package was developed by multiplying the

number of each type AGE used in the deployment package configurations by the unit cost

of each AGE type and then summing the total. The unit costs used for the AGE carts are

those identified in Table 11 of Chapter II.

The deployment costs of each treatment were calculated by multiplying the estimated number of C-141s required to transport the AGE as explained in Phase III by the FY93 $40,005 in direct airlift costs that was developed in Chapter II.

Then the two costs are combined and graphed based on varying number of deployments to Southwest Asia.

Phase V. Evaluate Each Treatment in Terms of Availability, Deployability, and Acquisition Cost

Any scenarios that are clearly sub-optimal were identified as such. Also, results were separated by their factor levels (particularly configuration level). The intent is that decision makers can use this information to develop trade studies on the aircraft availability, deployment, and financial benefits of one AGE package compared to another.

Summary

This chapter included a review of the research questions and identified this thesis's predicted results. It also explained how this thesis determined which of the four variables results in statistically significant differences in aborted sorties.

In review, this thesis used a four factor, single response ANOVA technique. All four factors are treated as having a fixed effect. Configuration has four levels. MTBF has two levels. MTTR has two levels. Travel time has two levels. All interactions were included. Each treatment was replicated 15 times. The report has also examined the underlying assumptions of the ANOVA analysis. Normality is tested with a series of

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Normality plots of the residuals and a Wilks-Shapiro test value for each treatment.

Equality of variance is tested by a plot of the residuals against their treatment means and with the Bartlett's test. Independence of each replication is tested by a plot of the residuals vs. their treatment replication number and by introducing a new factor, replication number, into the ANOVA analysis as a main effect with no interactions. This factor has 15 levels and is treated as a blocking variable.

Finally, this chapter includes an explanation of how deployment footprint and costs for each treatment were derived. In the next chapter, the results of these procedures are reported.

IV. RESULTS

Introduction

This chapter reports the results this thesis. The discussion starts with observations generated regarding the execution of the methodology described in the previous chapter. Then the chapter reports the primary results to the research questions first proposed in Chapter I and continues by analyzing these results. Finally the chapter closes by reviewing the results of this thesis.

Intermediary Findings

Verification of Simulation Model

When running the simulation as close as possible to the conditions identified in Experiment 42 of Carrico (1996), the mean PCM was found to be 13.4% with a sample standard deviation of 1.8%. Carrico reported an average PCM to be 9.5% with a standard deviation of 1.7%. The results of the confidence interval test explained in Chapter III are included in Table 17 and show a statistically significant difference in the PCM results of each report. The difference is estimated to be 3.9 percentage points. This is not desirous as it raises questions as to why a difference exists between what was planned to be identical scenarios. However, the relatively small magnitude of the difference suggests that the problem is not a fatal flaw in the simulation processor, but a lack of complete knowledge regarding the input parameters used by Carrico (1996). Although the majority of input parameters were identified by Carrico, some were omitted in the report. The principle researcher in charge of operating the simulation for the Carrico study, Eric Zahn

of TASC, Inc., claims that Experiment 42 was run using an aircraft mission flight time mean of 1.2 hours—not the 1.8 hours as had been originally indicated (Zahn, 1997b). When the simulation was run again using 1.2 hours, the mean PCM was 9.1% with a standard deviation of 1.9%. In this case, the difference between Carrico's results and the results of this thesis was less than one half of one percentage point and the 95% confidence interval contains zero. With the additional unpublished information about the flying mission duration (Zahn, 1997b), the differences between Carrico's (1996) results and those reported here are statistically insignificant. Consequently, this thesis can reproduce the same results reported in Carrico's study (1996) provided that all the pertinent information is collected from the report or the researchers involved with the report.

Table 17. Carrico's Experiment 42: Difference Between This Thesis and Carrico's Results

Attribute	Difference in PCM (with 1.8 vs. 1.2 flying hours) (percentage points)	Difference in PCM (with 1.2 vs. 1.2 flying hours) (percentage points)
95% CI UCL	4.8	0.5
Mean difference	3.9	-0.4
95% CI LCL	3.0	-1.3

In additional to these concerns, a programming discrepancy between the model desired for this research and the MASS simulation model was uncovered during execution of the experimental treatments. The MASS model includes a power check process at midnight. Each idle and fully operational aircraft undergoes a 15 minute diagnostic check which requires auxiliary power and air conditioning. Ideally, the model

would have been coded to identify one each of any AGE cart that had these two functions just as all other aircraft repair processes were coded. However, the simulation programmers specifically required a -60 generator and a -10 air conditioner for the power check process. Unfortunately, this caused the simulation to crash when all -60s or -10s were replaced by CGAC or MAGSS units.

Since the simulation code could not be altered, it was initially suggested that adding a few dummy -60s and -10s to the AGE shop resources might alleviate the problem. In fact, this method was used in the studies by Carrico (1996) and Zahn (1995) according to Zahn (1997a). However, this approach would create bias in the results since Treatments One through Eight would be performing power checks by using their primary AGE assets while Treatments Nine through Thirty-two would not. Since AGE failures are modeled by determining the number of operating hours between failures, adding this process would accelerate the frequency of AGE failures in treatments one through eight.

Instead, this thesis added the dummy -60 generators and -10 air conditioners as recommended but also decreased the time of each power check to an almost infinitesimally small duration for all treatments. As such, a bias still exists but its effects have been severely limited. Unfortunately, the model no longer considers the real effects of these nightly power checks. To see if there was a difference between these two simulation models, a statistical test was developed. Treatments one through eight were performed a total of 30 times each. Fifteen replications of each treatment were made with the power check duration set at 15 minutes. An additional 15 replications were made with the power check duration set at 3.6 seconds. The null hypothesis was that the true

mean difference of each pair was zero. The alternate hypothesis was that the true mean difference of each pair was something other than zero. A Paired T-Test of the differences between each of the 120 pairs was considered as our test statistic. This test assumes that the data consists of 120 independently selected pairs and that the differences between each pair are normally distributed with a common variance (Devore, 1995:367). However, when the number of pairs becomes large (over 30) then the assumption that the differences are from a normal distribution is not necessary because of the Central Limit Theorem. In this case, a Z-test may be used to replace the T-Test (Devore, 1995:370). When using a two-tailed 95% confidence level, the critical values of Z are ±1.96. The decision rule is that if the observed Z value is greater 1.96 or less than -1.96, the null hypothesis is rejected. The results are summarized in Table 18.

Table 18. Paired Z-Test for PCM no Power Checks Minus PCM with Power Checks

Mean:	-0.5741
Standard Error:	0.2785
Z observed:	-2.06

Since the observed test statistic value is outside of the range generated by the two-tail critical values at a level of $\alpha=0.05$, we reject the null hypothesis that the two paired populations have the same mean. Therefore, we have evidence to support that a statistically significant difference exists between the results of each of the two processes at the 95% confidence level. The average PCM differences were approximately one half of one percent. Although any difference is undesirable since it distorts our interpretation of the real flightline maintenance processes, the magnitude of this difference is small.

Therefore, the limitations existing in the power check process of the MASS simulation were handled with relative success.

Validation of ANOVA Assumptions

In order for ANOVA to be used properly, the assumptions of the ANOVA technique must be validated. Specifically, the error terms (residuals) must be normally distributed within each treatment, must have constant variance for all treatments, and must be independent (not serially correlated) (Neter, 1996:759-762).

Normality

Appendix A contains the normality plots for the residuals of each treatment. The residuals were created by subtracting the mean of each treatment from the value of each replication within the treatment. When the residuals are ordered and graphed against a rankit scale (z-statistic score values), they should form a straight line. Deviation from a straight line indicates deviation from normality. Also, any graph with a Wilks-Shapiro statistic value less than 0.895 is cause for concern.

Reviewing the normality plots in Appendix A yields a few conclusions. First, only two of the traditional, MAGSS, and CGAC configuration treatments appear other than normal. The first one is Treatment 4. Its Wilk-Shapiro statistic value is 0.8874 which is just 0.0076 less than the critical value of 0.895. The normality plot also showed a deviation from the desired straight line. Since the ANOVA procedure is robust to moderate departure from normality, such a small departure from normality should be minimal. The only other departure from normality for the first three configurations is

found in Treatment 23 and is caused by a single extreme value. In contrast, six of the eight treatments for the combined MAGSS & CGAC configuration appear to be other than normal. These six are Treatments 25, 26, 28, 29, 30, and 32. Treatments 25 and 26 are caused by a single extreme value similar to the problem found in Treatment 23. Treatments 28, 30, and 32 have much more pronounced departures from normality. Treatment 29 has a very slight departure from normality. The departures from normality are handled in the section entitled remedial measures.

Constancy of Variance

The ANOVA technique requires that the variance in each treatment is identical. Both graphical and quantitative methods exist to check this requirement. One common graphical method is to plot the residuals against the mean of each treatment (Figure 5). Some visual evidence indicated that the largest treatment means also contained the largest variance. It is not uncommon for variance to increase in a systematic way as the treatment mean increases (Neter, 1996: 110). A subsequent check of the correlation between the absolute value of the residual and the treatment mean revealed an r^2 value of only 0.1678. Therefore, no evidence exists to conclude that the increase in variance was due to an increase in treatment mean.
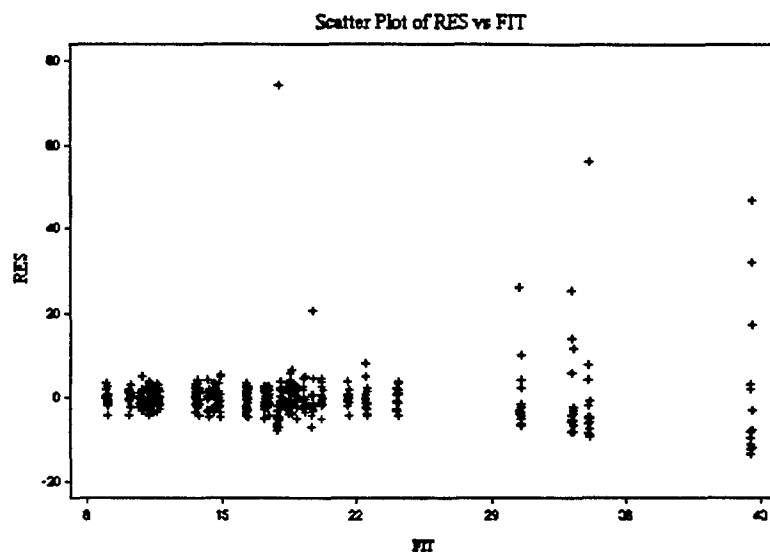
Figure 5. Residuals vs. Treatment Means

While reviewing the output, a new concern arose that the variance for the

treatments corresponding to the MAGSS & CGAC combination (Treatments 25-32)

seemed to be greater in magnitude than the other treatments (Treatments 1-24). This

hypothesis was checked graphically in Figures 6 and 7. Indeed, the treatments

corresponding to the combined MAGSS & CGAC configuration (Configuration Number

3 in Figure 7) exhibit much greater variability than their counterparts. This differences

posed a great threat to the applicability of an ANOVA analysis and is dealt with in the

section entitled remedial measures.
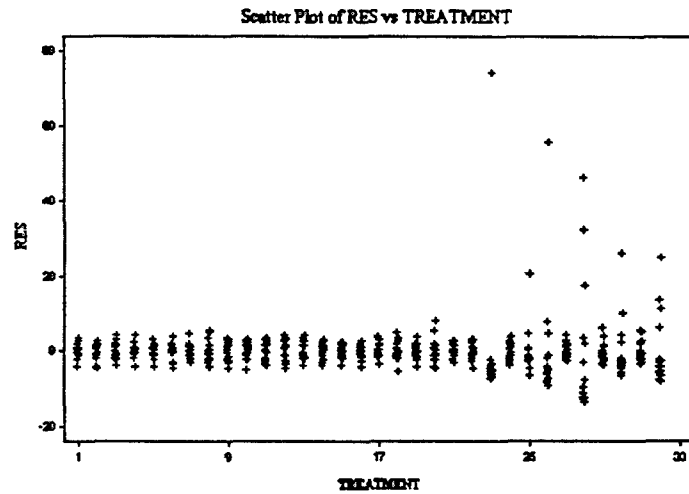
Figure 6. Residual vs. Treatment Number
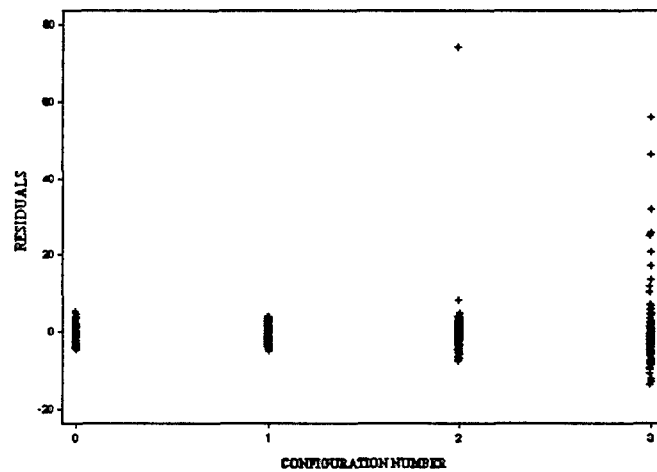
Figure 7. Residuals vs. Configuration

Independence

The first replication of each treatment started with the same random number seed.

Since each treatment began with the same random numbers, it is possible that a time

sequence effect may have been created. If true, the results of the first replication may not

be independent from one another. An induced correlation may exist in PCM values. To

test this possibility, this thesis used a sequence plot of the residuals (Figure 8). The goal of the plot is to identify whether any trend exists in the residuals based on their replication order (Neter, 1996:104). No trend is apparent. Therefore, the assumption of independence seems reasonable. However, the replication number effect is reintroduced in the ANOVA analysis in the latter portions of this chapter.
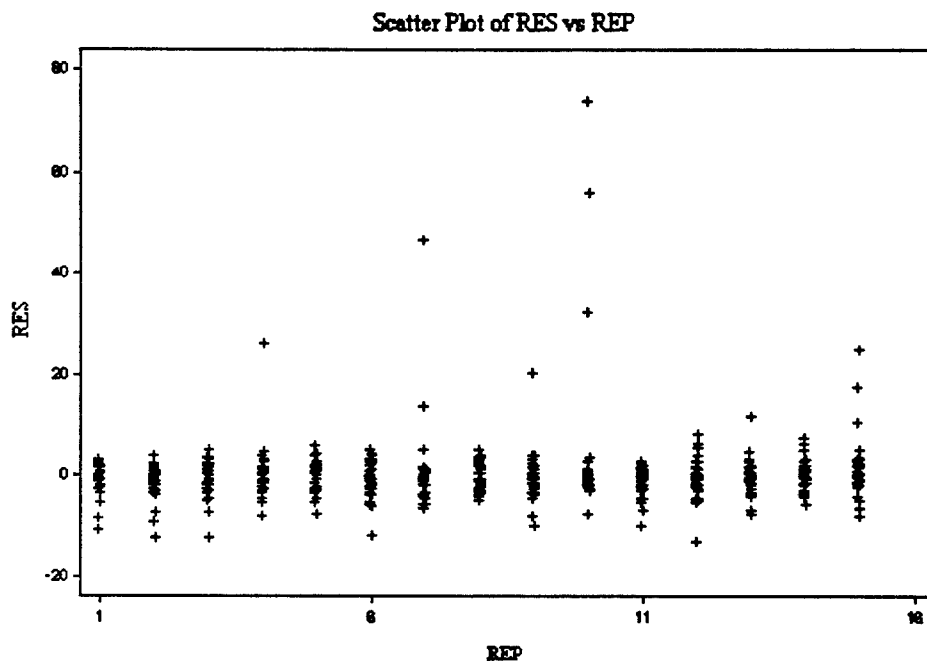
Figure 8. PCM Residuals vs. Replication Number

Remedial Measures

The problems identified with the constancy of variance may have been overlooked had each treatment been normally distributed. This is because the usage of equal sample sizes for each treatment minimizes the effect of unequal variance in fixed effect ANOVA (Neter, 1996:938). However, the combination of nonnormality and

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unequal variance precludes the use of the entire set of cases without some remedial measures. Since the primary offenders of these two assumptions come from the combined MAGSS & CGAC configuration, dropping this configuration from our analysis would allow me to proceed with the ANOVA. The decision to drop the statistical testing on the combined MAGSS and CGAC (Treatments 25 through 32) was made. Therefore, the statistical conclusions apply only to the pure configurations of traditional, MAGSS, and CGAC configurations. The only other departure of equality of variance and normality was due to Replication Number 10 of Treatment 23. Table 19 summarizes the results of the Bartlett's equality of variance test on the remaining cases when the identified cases are omitted. The null hypothesis is that the true variance of each treatment is equal to all the other variances whereas the alternate hypothesis is that at least one of the true variances is not equal to all the others. When only the cases from Treatments 25 through 32 are omitted, the conclusion is to reject the null hypothesis that all variances are equal. However, when Replication Number 10 of Treatment 23 is also omitted, a P-Value of 0.4859 indicates that no evidence exists to reject the null hypothesis. Also, the new Wilks-Shapiro test statistic value for Treatment 23 when Replication Number 10 is omitted has a value of 0.9719. Therefore, omitting Replication Number 10 of Treatment 23 and all replications from Treatments 25 through 32 leaves us with 359 cases that do not break any of the assumptions of ANOVA. This thesis used only these 359 cases for the rest of the ANOVA analysis.

Table 19. Bartlett's Test for Equality of Variance

Omitted Cases	Test Statistic and Value	P-Value
Treatments 25 through 32	$\chi^2 = 437.46$	$< .0001$
Treatments 25 through 32 plus Replication Number 10 of Treatment 23	$\chi^2 = 22.57$	.4859

Had Replication Number 10 of Treatment 23 been included, a more robust ANOVA method that did not use the least squared error method may have been necessary. Methods such as the least absolute residual, iteratively reweighted least squares procedure, or least median of squares procedure all handle outliers more effectively than does the least squares method (Neter, 1996:417-418).

Research Findings

Using present range estimates as levels for our factors, do statistically and practically significant differences in the expected PCMs exist?

The results of the analysis of variance on the differences in PCM between the factors identified in Chapter I is included in Table 20. All of the main effects plus four of six first-order interactions and one of four second-order interactions were found to be statistically significant using an $\alpha = 0.05$. Coincidentally, when Replication Number 10 of Treatment 23 was included, the interactions A*D, A*C, and A*B*C were reclassified as statistically insignificant using an $\alpha = 0.05$. Also, when the ANOVA was performed adding replication number as a factor with no interactions, the introduction caused no differences in the identification of significant effects.

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Table 20. ANOVA Results of Factor Effects

SOURCE	DF	SS	MS	F	P
CONFIG (A)	2	362.00	181.00	35.40	0.0000
MTBF (B)	1	481.09	481.09	94.10	0.0000
MTTR (C)	1	477.43	477.43	93.38	0.0000
TRAVTIME (D)	1	4018.89	4018.89	786.09	0.0000
A*B	2	22.97	11.49	2.25	0.1050
A*C	2	51.10	25.55	5.00	0.0074
A*D	2	45.39	22.70	4.44	0.0125
B*C	1	286.19	286.19	55.98	0.0000
B*D	1	150.45	150.45	29.43	0.0000
C*D	1	8.42	8.42	1.65	0.2003
A*B*C	2	32.06	16.03	3.14	0.0436
A*B*D	2	8.44	4.22	0.83	0.4422
A*C*D	2	29.28	14.64	2.86	0.0569
B*C*D	1	12.26	12.26	2.40	0.1225
A*B*C*D	2	3.58	1.79	0.35	0.7096
ERROR	335	1712.69	5.11		
TOTAL	358	7702.24			

Statistically significant differences in PCM do not necessarily imply practically significant differences. In order to judge the practical significance of these differences, the treatment means must be reviewed. Table 21 includes the treatment means for all the treatments included in the ANOVA in the top half of the table plus all the treatments that were excluded in the bottom half. Treatment 23 was computed without the extreme value of 91.85 %.

Table 22 identifies all of the statistically significant effects and the highest and lowest levels of those effects. The effects have been sorted by the magnitude of the difference in PCM. The largest difference of an effect is 9.1 percentage points while the smallest is 1.9 percentage points. Several facts from Table 22 become quickly apparent. Three of the four main effects only cause about three percentage points difference between the highest and lowest levels. Although already identified as statistically

Table 21. PCM Means by Treatment

Treatment #	AGE TYPES	MTBF (operating hrs)	MTTR (hrs)	Travel Time (min)	MEAN PCM (%)
1	Traditional	Low	1	15	9.0864
2	Traditional	Low	1	45	16.383
3	Traditional	Low	5	15	13.802
4	Traditional	Low	5	45	21.617
5	Traditional	High	1	15	10.247
6	Traditional	High	1	45	14.383
7	Traditional	High	5	15	10.852
8	Traditional	High	5	45	14.926
9	CGAC	Low	1	15	11.296
10	CGAC	Low	1	45	17.333
11	CGAC	Low	5	15	14.691
12	CGAC	Low	5	45	24.148
13	CGAC	High	1	15	11.259
14	CGAC	High	1	45	16.358
15	CGAC	High	5	15	11.494
16	CGAC	High	5	45	17.494
17	MAGSS	Low	1	15	11.753
18	MAGSS	Low	1	45	20.321
19	MAGSS	Low	5	15	13.877
20	MAGSS	Low	5	45	22.556
21	MAGSS	High	1	15	11.815
22	MAGSS	High	1	45	18.938
23	MAGSS	High	5	15	12.725
24	MAGSS	High	5	45	18.630
				AVG:	15.256
25	MAGSS & CGAC	Low	1	15	19.741
26	MAGSS& CGAC	Low	1	45	34.123
27	MAGSS& CGAC	Low	5	15	18.185
28	MAGSS& CGAC	Low	5	45	42.580
29	MAGSS& CGAC	High	1	15	18.704
30	MAGSS& CGAC	High	1	45	30.580
31	MAGSS& CGAC	High	5	15	19.358
32	MAGSS& CGAC	High	5	45	33.272

significant, such low differences in magnitude raise questions about the practical

significance of these factors. In fact, these findings can be loosely compared to Carrico's

(1996) findings where he found little difference in PCM when varying the levels of

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MTBF and MTTR individually (Carrico, 1996:22-25). However, such a view was short-sighted when the interactions of the two factors are considered. For example, the difference in mean PCMs between the highest and lowest levels of the effect MTBF*MTTR was 4.6 percentage points which is equivalent to approximately 50 additional aircraft flown in the 30 day period (of the 1080 sorties). It is reasonable to conclude that this is a large enough difference that a true prediction of PCM is not available until better ranges of MTBF and MTTR are available.

Table 22. PCM Means by Statistically Significant Effect Level

Effect	Lowest Level	Mean	Highest Level	Mean	Diff.
Configuration * Travel Time	Traditional * 15 Minutes	11.0	MAGSS * 45 Minutes	20.1	9.1
MTBF * Travel Time	High * 15 Minutes	11.4	Low * 45 Minutes	20.4	9.0
Configuration * MTBF * MTTR	Traditional * High * 1 Hour	12.3	CGAC * Low * 5 Hours	19.4	7.1
Travel Time	15 Minutes	12.3	45 Minutes	18.6	6.3
MTBF * MTTR	High * 1 Hour	13.8	Low * 5 Hours	18.4	4.6
Configuration * MTTR	Traditional * 1 Hour	12.5	MAGSS*5 Hours	17.0	4.5
Configuration	Traditional	13.9	MAGSS	17.0	3.1
MTTR	1 Hour	14.1	5 Hours	16.8	2.7
MTBF	High	14.5	Low	16.4	1.9

MTBF and MTTR are not the only factors that require such analysis. Consider the factor travel time. Travel time is listed in three of the top four effects. The largest interaction is Configuration*Travel Time with the largest difference in levels causing a 9.1 percentage point difference in mean PCM. In fact, the estimated PCM at the highest level is almost twice that of the estimated PCM at the lowest level. All four of the factors studied are involved in main effects or interactions that cause statistically and relatively large differences in the estimate for PCM.

At this point, the reader may believe that no statements can be made as to one configuration level being superior to another. In general, this is true. However, if an additional assumption is introduced where the treatment means are compared while holding MTBF, MTTR, and Travel Time at the same level, some additional results are available. Before these are introduced, a more careful explanation of this procedure is presented. By setting all of the three factors at the same level, this thesis assumes that, say, the MTBF of both the MAGSS, CGAC, and traditional carts are all at the higher level. This may not actually be the case. In reality, the CGAC's true MTBF may be closer to the low level range while the MAGSS and traditional carts may be closer to the high level range. However, when the conditions are uniformly applied, the results of Figure 9 become apparent. Treatments 8, 16 and 24 are plotted with the same x-axis vale of zero. Treatments 1, 9, and 17 have an x-axis value of one. Treatments 2, 10, and 18 have been grouped together and number three, etc. The "T" represents the traditional configuration. The "C" represents the CGAC configuration. And the "M" represents the MAGSS configuration. Notice that the traditional configuration has a lower PCM in all cases. The MAGSS configuration and the CGAC configuration exchange second and third place depending on the grouping. Thus, the traditional configuration is slightly superior when establishing this rather rigid additional assumption.
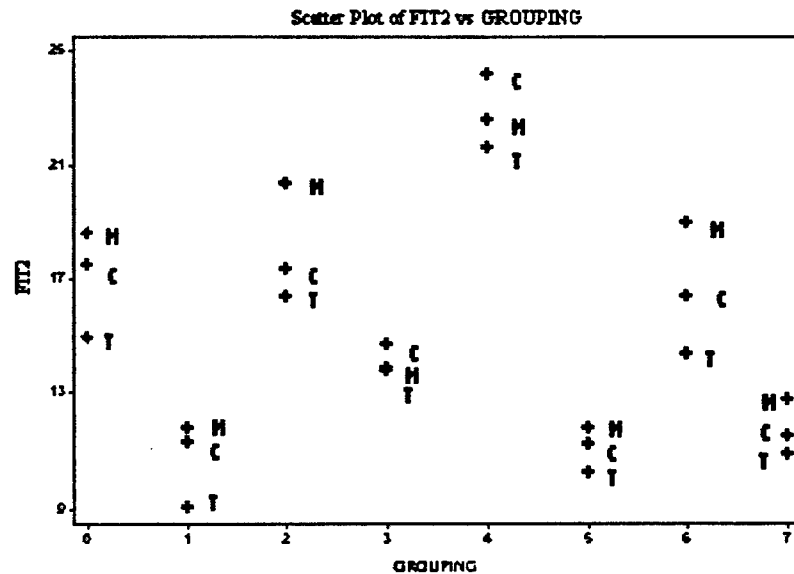
Figure 9. PSA Means Holding MTBF, MTTR, and Travel Time Constant

As was explained above, the means for Treatments 25 through 32 were greater

than any of the comparable treatments under the other configurations. This is due to the

large amount of extreme values. These extreme values are caused when aircraft repair

demand exceeds AGE resources. The number of aircraft needing repair escalates as the

queue for AGE increases. Eventually, PCM becomes very large.

A combined MAGSS and CGAC option could probably maintain equilibrium if a

total of more than six carts MAGSS or CGAC carts were used. However, the wisdom of

such a configuration is suspect since the six pure MAGSS or six pure CGAC

configurations do the job effectively without the added costs.

Setting all of Treatments 25 through 32's difficulties aside, the treatment means of

the combined MAGSS and CGAC configuration are still consistent with the findings

stated earlier in this section. The effect that travel time had on the PCM treatment mean

was still the most noticeable main effect.

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What is the deployment footprint for each AGE design option?

The physical deployment footprint for each configuration is listed in Table 23 as is an estimated number of C-141 aircraft required to transport these AGE cart packages. These estimates only include the carts themselves and do not include the personnel, tools, technical manuals, and parts required to maintain these AGE carts. The MAGSS configuration has the lowest total weight, volume, floor space, and number of C141s required. However, this configuration also has the highest density and the highest floor pressure. The high density may cause the aircraft to exceed weight limitations before exceeding the more common space limitations. Also, the pressure on the floor of the aircraft has more than doubled. It should also be kept in mind that this pressure would not be evenly distributed on the floor if the MAGSS units were rolled onto the aircraft. In this case, the entire weight of each 6,500 pound piece of AGE would supported by the area under each of the tires. It is doubtful, however, that this pressure would cause too many problems since the Air Force typically designs its aircraft to carry the much heavier Army tanks (whether the AF moves tanks by air or not).

Table 23. Deployment Footprint Results

Configuration:	Weight (lbs.)	Volume (cu. ft.)	Density (lbs/cu. ft.)	Floor Space (sq. ft.)	Pressure (lbs./sq. ft.)	C141 Sorties
Traditional	91980	10421.0	8.8	1905.5	48.3	2.0
CGAC	71700	6875.7	10.4	1289.7	55.6	1.3
MAGSS	54620	3802.8	14.4	664.6	82.2	0.7
MAGSS & CGAC	57480	4831.4	11.9	860.0	66.8	0.9

What are the costs involved with each alternative?

The direct costs required to purchase a full complement of each AGE configuration package for a squadron of 18 F-16 aircraft are identified in Table 24. Also included are the direct costs to deploy the AGE equipment on a single deployment to Cairo West, Egypt. As the number of deployments rises, the total life cycle cost will increase. Figure 10 provides a look at this tradeoff. This figure provides the combined direct costs of acquisition and deployment as the number of one-way trips to or from Southwest Asia are increased. The range of deployments was graphed from zero to 120. Since AGE can be in the inventory for potentially 30 years, this range assumes that an average of no more than two round trip deployments per year. Even with one round trip, the total life cycle costs of the CGAC are less than the traditional configuration. It requires 13 round trips for the MAGSS to be cheaper than the traditional AGE option. It requires 27 round trips for the MAGSS to be cheaper than both the traditional and the CGAC configurations. This analysis is sensitive to the acquisition costs of the CGAC especially considering that the estimate was created with the program manager's knowledge but not her assistance. Indirect costs have not been included in the acquisition or deployment costs. It is unclear how these costs would influence one configuration level above another. Therefore, *the break-even points of one, 13, and 25 should only be considered rough estimates since uncertainty exists in terms of pricing changes in the last four years and the effects of indirect costs.*

Table 24. AGE Configuration Acquisition and Deployment Direct Costs

	Acquisition Cost (FY93 $Millions)	Cairo Deployment Cost (FY93 $Millions)
Traditional	$ 1.18	$ 0.08
CGAC	$ 1.21	$ 0.05
MAGSS	$ 2.45	$ 0.03
MAGSS&CGAC	$ 2.00	$ 0.02
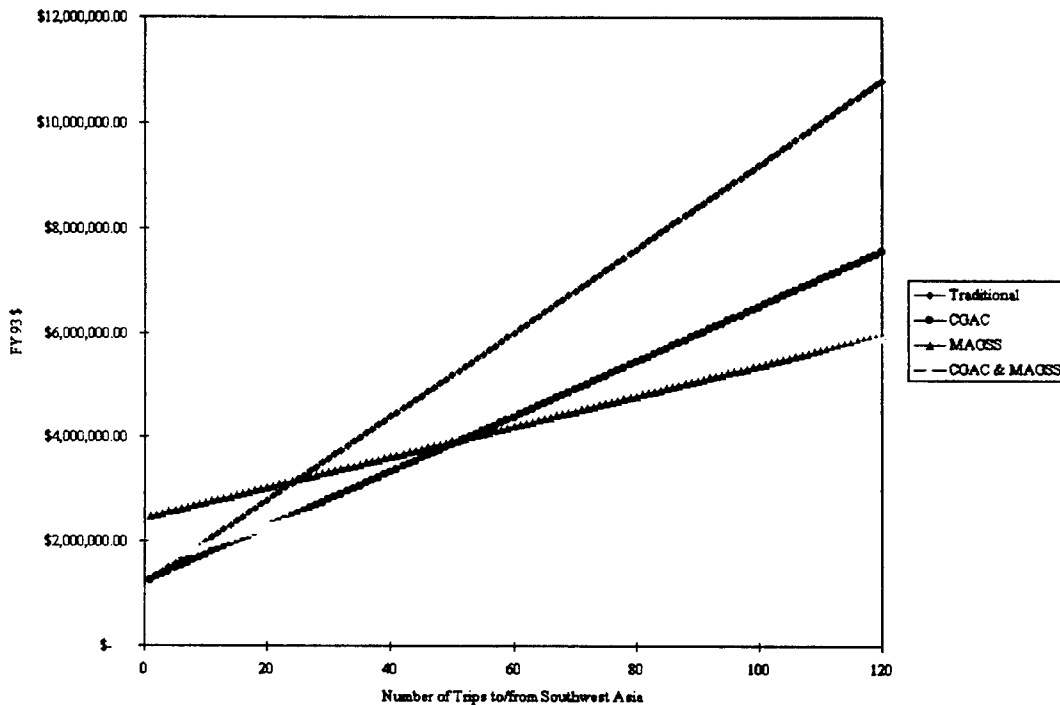
Figure 10. Direct Deployment and Acquisition Costs as Deployments Rise

Which options are efficient in overall value?

Several issues must be considered when addressing which configuration promises

high potential. Certainly the MAGSS configuration has the most dramatic reduction in

deployment footprint. Over 37,000 pounds, 6,600 cubic feet, and 1,200 square feet of

floor space of directly attributable equipment have been eliminated to say nothing about a

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potential reduction of indirect equipment. Also, the cost to deploy the AGE has been reduced by over $50,000 for a single deployment to Southwest Asia. These benefits have their price. Acquisition costs for a squadron's worth of this specialized equipment is over $1,250,000 more expensive than the traditional AGE carts. This additional cost is, however, recouped if the equipment is taken on over 13 round trip deployments over its lifetime.

A less aggressive acquisition program might prefer the benefits of the CGAC. Over 20,000 pounds, 3,500 cubic feet, and 615.8 square feet of floor space are reduced. Also, the CGAC provides savings over the traditional configuration after the first deployment.

Potentially, a balance might be made between the expensive but efficient MAGSS carts and the more affordable CGAC carts. However, the efforts during this thesis project to create such a balance were unsuccessful. A reported attempt at using 4 MAGSS and 2 CGAC (Treatments 25 through 32) and an unreported attempt at using 2 MAGSS and 4 CGAC proved too risky. Both scenarios resulted in unacceptably high levels of aircraft schedule cancellations.

It is impossible to correctly identify which of the configurations is best in terms of aircraft availability because the estimates for the other three factors identified in this study have statistically and practically significant differences in their estimated ranges. When MTBF, MTTR, and travel time are held at the same levels, the traditional AGE configuration is best. However, the rationale for such an analysis is questionable at best.

Summary

This chapter began with a discussion of intermediary findings. Specifically, the difference between Carrico's (1996) results and the results of this thesis when recreating a case developed by Carrico were statistically significant when exclusively using the Carrico report. The differences were statistically insignificant when the results were repeated using additional information supplied by the original researchers. Therefore, the simulation used in this study can recreate the results of the Carrico (1996) report given enough information about how the experiment was performed. The power check operation of the simulation was incompatible with the scenarios to be to be simulated. Therefore, the duration of the power checks were set at nearly zero in order to remove their influence on the results.

The chapter continued with an assessment of the assumptions of ANOVA. Normality, constancy of variance, and independence were reviewed. Normality and constancy of variance assumptions were violated by the data in the combined MAGSS/CGAC configuration. This data was omitted from further analysis. Also, one data point from Treatment 23 was omitted as well. However, the effects of leaving the data point in the data set were later considered and found to be limited.

All of the four factors and several of the interactions being investigated were found to have statistically and practically significant differences in PCM when their levels were varied. When MTBF, MTTR, and travel time were allowed to vary freely, no one level of the factor configuration was found to be superior. When MTBF, MTTR, and

travel time were locked in step, the traditional configuration was found to have the best PCM for each grouping. The wisdom of this added assumption is suspect.

All three AGE configuration options predicted relatively large improvements in deployment footprint measures. The MAGSS configuration had the best deployment footprint but also had a much higher acquisition cost than the traditional configuration. This difference in cost was worthwhile if the equipment was taken on more than an estimated 13 round trip deployments in the course of its service life. Although the CGAC configuration did not have as large a deployment footprint savings as the MAGSS options, the savings were nonetheless practically significant. The CGAC configuration was less expensive than the traditional configuration after the first deployment. However, the MAGSS configuration was superior to the CGAC configuration in terms of direct FY93 costs after an estimated 27 round trip deployments to Southwest Asia.

V. CONCLUSIONS

Introduction

This chapter begins by interpreting the results reported in the previous chapter and drawing some conclusions from these interpretations. Next, the discussion turns to the implications that the results and conclusions have on the Air Force. Suggestions for further research are identified. The chapter concludes with a brief summary of this thesis.

Interpretation/Conclusions

By the research questions

Using present range estimates as levels for our factors, do statistically and practically significant differences in the expected PCM exist?

AGE configuration, MTBF, MTTR, and travel time ranges were all found to produce statistically and practically significant differences in PCM when they are allowed to vary across their estimated range. This conclusion is especially true when the interactions of these four factors are considered.

No one best AGE design configuration was found to exist. Additional research is required in estimating MTBF, MTTR, and travel time for each of the configurations before any strong statements can be made regarding which alternative is superior in terms of F-16 aircraft availability during surge conditions. Additional effort toward narrowing the range of travel time will greatly reduce the uncertainty in prediction of aircraft availability.

It is not surprising that the estimate for the time it takes AGE to move from aircraft to aircraft or from aircraft to the AGE shop is so critical. A single piece of AGE could be transported many times each day. While it is being moved, it is unavailable to service aircraft. For example, suppose a piece of AGE starts the day in the AGE shop, travels to the first aircraft and services it, returns to the AGE shop, travels to the second aircraft and services it, travels to the third aircraft and services it, and then returns to the AGE shop. The AGE cart has spent an hour and fifteen minutes in transport if the one way travel time delay is fifteen minutes and three hours and 45 minutes if the one way travel time delay is 45 minutes. This total travel time that occurs daily can to be greater than the average repair time. Also, the travel time occurs each day whereas AGE failures occur only occasionally in the days, weeks, or months of a military operation. The conclusion that travel time is so critical is also consistent with Carrico's (1996:21-22) study and with much of the literature in the time-motion field of human factors engineering.

Because of the lack of normality and equal variance in the combined CGAC and MAGSS configuration, only the traditional, CGAC, and MAGSS configurations were included in these results. The reason that the mixed option was unacceptable was that an insufficient number of resources were available to satisfactorily keep pace with aircraft repair needs. Specifically, the number of requests for a MAGSS that were pending was unacceptably high. It is unclear which of the services provided by the MAGSS were being demanded, but the combined demand was too great. When a lack of equilibrium between resources and demand occurs, a spiraling shortage can occur. This is because

those aircraft that are still operating start flying every mission of every day which places them in even further risk of joining the rest of the aircraft that have broken and are waiting to be repaired.

What is the deployment footprint for each AGE design option?

The deployment footprint measurements are listed in Table 23 in Chapter IV. The MAGSS configuration was the best in terms of deployment footprint. The CGAC and the combined CGAC and MAGSS configurations also had relatively large reductions in the deployment footprint compared to the traditional configuration.

What are the unit costs of the AGE carts and the airlift costs involved with each alternative?

The acquisition and deployment costs of the AGE configurations are listed in Table 24 of Chapter IV. If the AGE package never deployed during its service life, then the traditional AGE package is the cheapest option. If the AGE package is subjected to even a single deployment in its service life, the CGAC option becomes the least expensive. This option remains the best value unless the AGE package is expected to deploy on over 10 round trip deployments. In this case, the combined CGAC and MAGSS option becomes the least expensive. However, the combined CGAC and MAGSS option was found to be unacceptable. Therefore, the CGAC configuration is actually the least expensive between one and 27 round trip deployments. After that, the MAGSS configuration is the least expensive. These estimates do not include indirect costs of different AGE configurations and use AGE costing data from 1993.

In light of the end of the cold war, the increase in military operations other than war, and the reductions in overseas basing, it seems reasonable to believe that new AGE packages will be deployed from and then returned to the United States at least once and quite possibly over 27 times. As such, the CGAC and MAGSS options are recommended given the direct costing data considered in this analysis.

Which options are efficient in overall value?

The hybrid configuration that includes MAGSS and CGAC units was found to be inefficient because of excessive aircraft schedule cancellations. The traditional AGE configuration is not very efficient in terms of deployment footprint and acquisition costs since its direct costs using FY93 estimates are greater than any other option after the first deployment. However, the traditional AGE configuration was associated with the some of the lowest levels of aircraft schedule cancellations (however small the margin). An aggressive campaign to reduce total life cycle costs would probably recommend the MAGSS package while a more acquisition cost-conscious program would recommend the CGAC configuration and risk that the AGE packages were deployed for less than the estimated 27 round trips across the world. It is important to remember that *the number of trips necessary for the differences in acquisition costs of two configurations to be overshadowed by the differences in deployment costs is an estimate based on FY 93 direct cost data only.* The methodology used in its creation can be reapplied as more current and complete cost information is acquired.

By other findings

The results of Treatments 25 through 32 and the extreme value in Treatment 23 are a reminder that very bad things can happen to an air base if an insufficient quantity of AGE exists to service the needs of the broken aircraft. Even an apparently large enough quantity of AGE can be insufficient when an unusually high quantity of AGE carts or aircraft break in a single day. If the AGE resources were already stretched to near the limit, the aircraft schedule may never fully recover. Therefore, when the factor level estimates become sufficiently narrow to form irrelevant differences in PCM, renewed attention should be placed upon AGE utilization. After all, two AGE configurations might have nearly the same PCM estimate but might have vastly different levels of risk associated with them. AGE utilization rates are a good operational indicator of the risk associated with a given AGE package.

The latest information about the F-22 support equipment program as discussed in Chapter I offers hope that care is being taken to reduce the size of deployment packages for future aircraft acquisitions. Extra attention to two level maintenance, improved reliability, on-board maintenance servicing systems, and multifunction AGE has reduced the size of the AGE package.

Implications for the Air Force

The implications of the findings of this thesis are quite profound. Consider the following examples. In Chapter I, it was identified that over 390 C-141 equivalent sorties were flown to provide the necessary personnel, support equipment, and spares in the early phases of Desert Shield/Desert Storm (Aeronautical Systems Center, 1993:2). Also in

Chapter I, it was determined that 22% of the weight of a typical composite wing deployment was directly attributable to AGE carts. Suppose that this also meant that 22% of the 390 C-141 equivalent sorties were necessary to haul the AGE carts. That would mean that over 85 C-141s were used to transport AGE. If the overall reduction in the number of C141s needed to transport AGE was as dramatic as our weight reduction of switching from a traditional to a MAGSS configuration for one squadron, the number would be reduced to just over 50 C-141s. That is a savings of 35 C-141 sorties in the early days of a conflict. And remember this savings of 35 C-141 sorties is based on an estimate that AGE comprises just 22% of all equipment deployed. Other sources estimate that the *percentage of equipment attributable to AGE may be as high as 70%.*

Or, assume that each of the 28 squadrons sent to Desert Shield/ Desert Storm required just two C-141 sorties to transport their AGE carts. Switching to a MAGSS configuration might bring the 56 C-141 sorties down to just 20. Again, the result is a savings of about 35 C-141 sorties. Although financial constraints limit much of the Air Force today, the military effectiveness of freeing up 35 additional sorties in the early days of a conflict is very enticing. These savings are particularly attractive in a time when flexibility in deployment operations are being particularly emphasized with the introduction of the Air Expeditionary Force. In fact, it is this thesis's recommendation that the Air Expeditionary Force Battlelab study the implications of MASS concepts as should the F-22 and JSF SPOs.

Besides airlift savings, improvements in the effectiveness of aircraft availability are suggested but not verified. The time it takes AGE carts to travel to and from their

work plays a big role in how well the aircraft are maintained. Two recommendations on how to improve aircraft availability are suggested. First, careful control of the whereabouts and status of AGE is recommended. If an AGE resource pool controller was aware that a piece of AGE was almost ready to be released from a maintenance job, the controller could notify a tug driver to immediately begin driving over to the parking spot to retrieve the AGE and place it into service on another job. Second, the acquisition community could provide powered wheels to future AGE carts so they could be driven from one maintenance job to the other without waiting for a tug.

Both the MAGSS and the CGAC packages seem promising thus far. These technologies which are almost capable of full-scale squadron-level testing should be further studied along with other less developed MASS technologies like the modular MASS cart.

Finally, the AGE community should recognize that AGE acquisition dollars are not the only criteria for evaluation when planning for the initial purchase or replacement of AGE. Total life cycle costs which include AGE deployment costs should be estimated.

Suggestions for Further Research

This thesis investigated the effects of four factors and their interactions on PCM. This list is by no means all inclusive. Other factors could be systematically set at different levels to observe their effects across their estimated range. Such options include: flying schedule times, flying mission duration, duration of integrated combat turns, aircraft failure mode rates and repair durations, maintenance personnel levels, spare

parts levels, AGE and maintenance personnel needed for each aircraft failure, etc. In particular, future studies could more tightly limit access to spare parts and maintenance personnel since both of these resources were modeled as being unconstrained in this thesis.

Ideally, when all fixed-level factor estimates have been calibrated to a tight enough range such that their effects do not vary the PCM, trade-off studies could begin. The PCM estimate could then be compared with the costs and deployment sizes already analyzed in this report. Therefore, cost, deployment size, and aircraft availability could all be compared between different scenarios of aircraft and support resources. Other areas such as safety and environmental impact could also be addressed. Such analysis is vitally important if total life cycle cost visibility is to ever become reality. This report has led the way for a methodology that can promise such future advances.

This thesis used only aircraft data on the F-16, so the results can be safely applied only to this aircraft. This report could be reapplied to the F-22 or JSF aircraft if reliability and maintainability data can be estimated. However, the AGE community should not wait until perfect information becomes available or risk that paralysis will force yet another generation of aircraft to have the same single-function carts.

As was indicated in Chapter I assumptions, this research treats AGE failures at the system level for each AGE type. Future research could perform component-level failure mode analysis and then apply the results by increasing the level of detail in the model.

Analytic models could be developed to match the output of the simulation. The analytic models could be developed by forming a complex set of equations that estimates

PCM. The coefficients of each linear term could be estimated using the data from the simulation model.

Three of the four factors used in this thesis were limited to only two levels. It is impossible to know how PCM would be affected by levels that were in between these two levels without performing further testing. Such an endeavor may attempt to go as far as creating a complete response surface mapping of the factors introduced herein.

As was indicated above, two simulations may be nearly identical in terms of PCM but have very different levels of risk. A study could be created to analyze the effects of AGE cart utilization on PCM risk.

Treatments 25 through 32 were unacceptable because the MAGSS carts were in too great a demand. However, it is nearly impossible to determine which set of the services provided by the MAGSS cart were so needed. A new simulation could be written that keeps better records of the types of AGE services requested by the aircraft maintenance personnel.

Summary of Thesis

In a time when the location of future military operations is difficult to predict and overseas basing is shrinking, the need for creative ways to reduce the deployment footprint is necessary. Support equipment is one of the largest categories of objects that are airlifted when a squadron deploys. Although recent initiatives such as the two level maintenance concept have helped reduce the deployment footprint of support equipment, AGE continues to be one of the largest single categories of support equipment. Both Headquarters, Air Mobility Command, and a committee in NATO have emphasized the

need for AGE combination and reduction. Two particular AGE reduction technologies were discussed—the MAGSS and the CGAC. Unfortunately, a great deal of knowledge must be developed before a formal trade-off study analysis can begin between any combination of these two technologies and the more traditional AGE cart packages. Some of the initial steps towards such a complete analysis are developed within this thesis. In particular, two key purposes to this thesis were developed to aid in this endeavor.

The first purpose of this thesis was to identify what aircraft availability factors need more precise estimates before adequate aircraft availability comparisons are possible. This thesis studied the effects of four factors on aircraft availability. The AGE design, the MTBF of AGE, the MTTR of AGE, and the travel time to transport the AGE around the flightline were used. It was discovered that the present estimates of these factors are too broad for trade studies that include an estimate of aircraft availability to begin. It is recommended that further field observation and data collection be accomplished before the merits of one AGE cart technology be compared to another.

The second purpose of this thesis was to collect as much information on other criteria which are likely to be in a trade study—such as the deployability and affordability of AGE. Although much of the information collected was a few years old, the data did suggest that new technologies can improve the deployment footprint and the combined cost of acquisition and deployment. A clear methodology was developed that could be expanded as complexity and detail are added.

Hopefully, this thesis will revitalize both professional and academic interest into the significant role that support equipment, in general, and AGE, in particular, play in the effective planning of deployed base operations. Only then will future decisions about support equipment procurement be based on fact and not convenience. Regardless, AGE will continue to impact aircraft availability in the United States Air Force—intentionally or not.

APPENDIX A. NORMALITY PLOTS

The following graphs are the normality plots of the residuals generated by taking the PCM observed values and subtracting the PCM treatment means. Each graph includes only one treatment. An approximate Wilk-Shapiro Test Statistic is also included. As an example, the graph on this page is the residuals of Treatment 1.
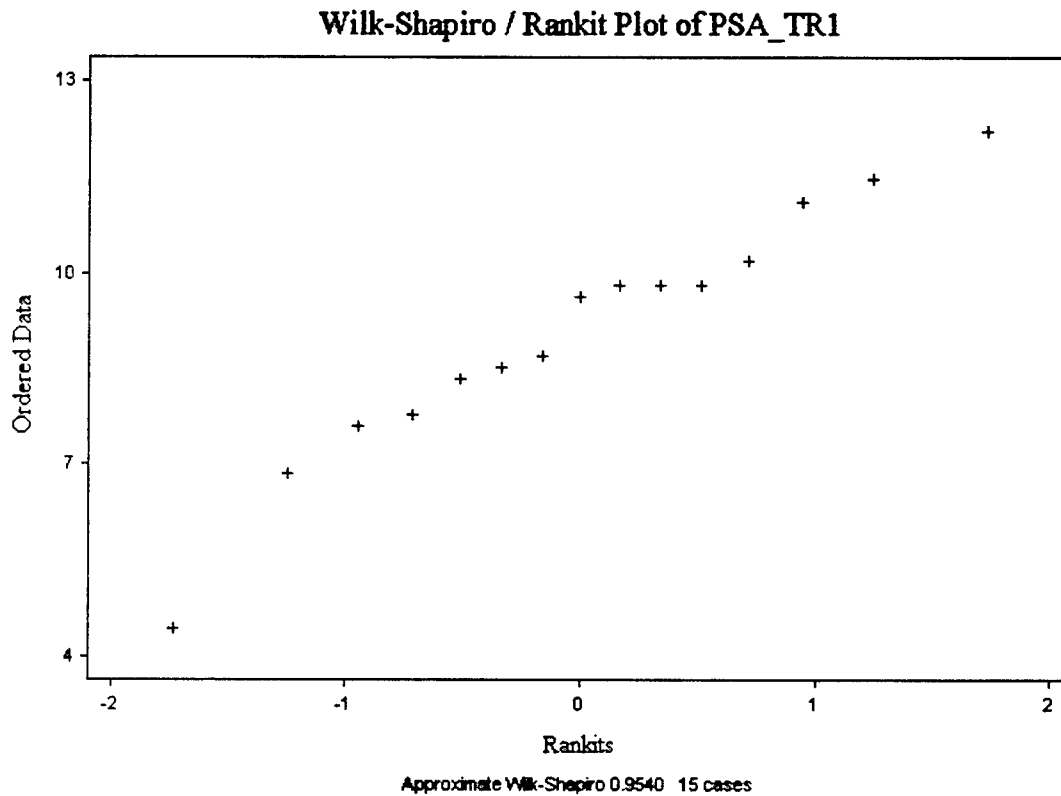
Wilk-Shapiro / Rankit Plot of PSA_TR1

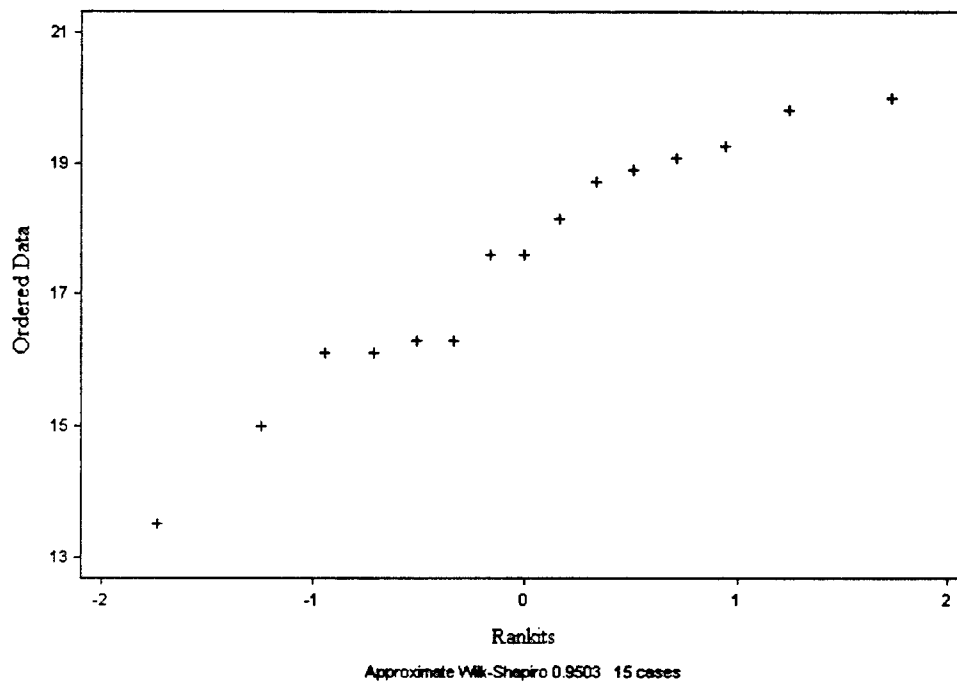Approximate Wilk-Shapiro 0.9540   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR2

Approximate Wilk-Shapiro 0.9100   15 cases

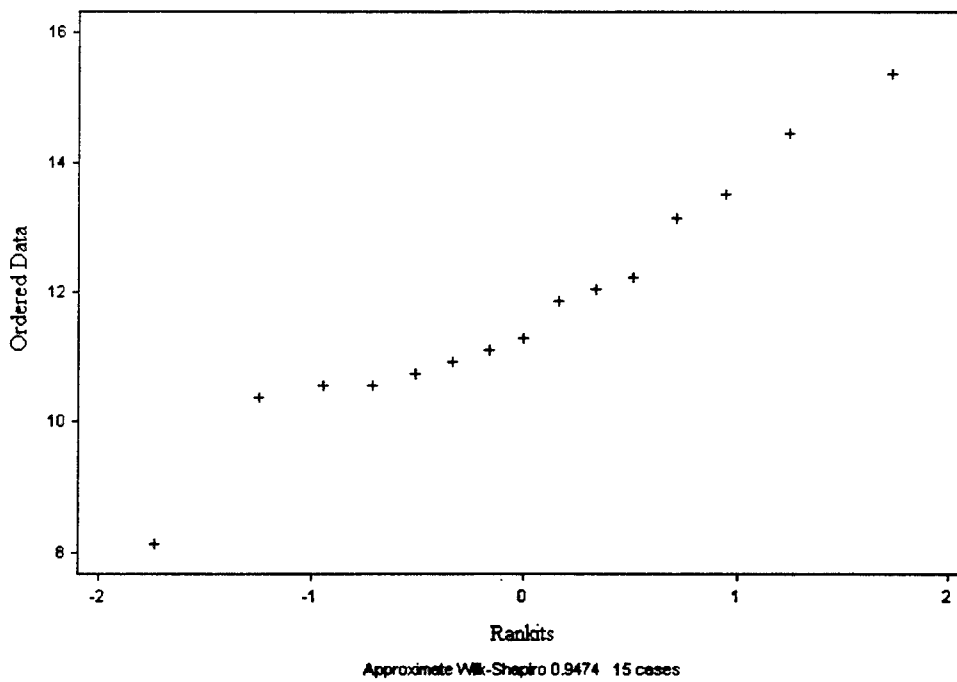# Wilk-Shapiro / Rankit Plot of PSA_TR3
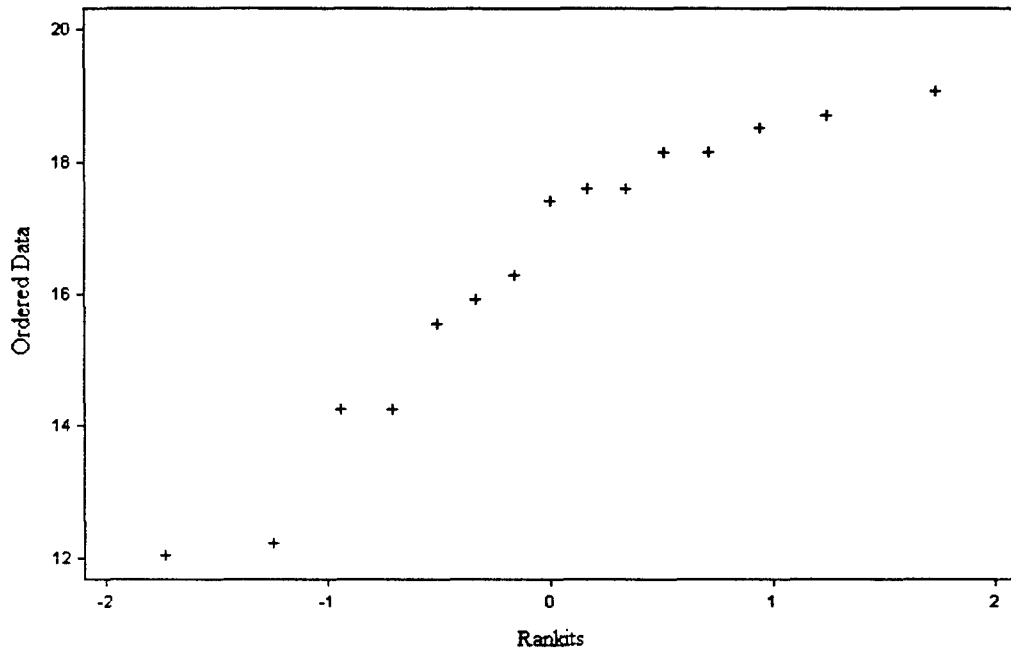
Approximate Wilk-Shapiro 0.9768   15 cases
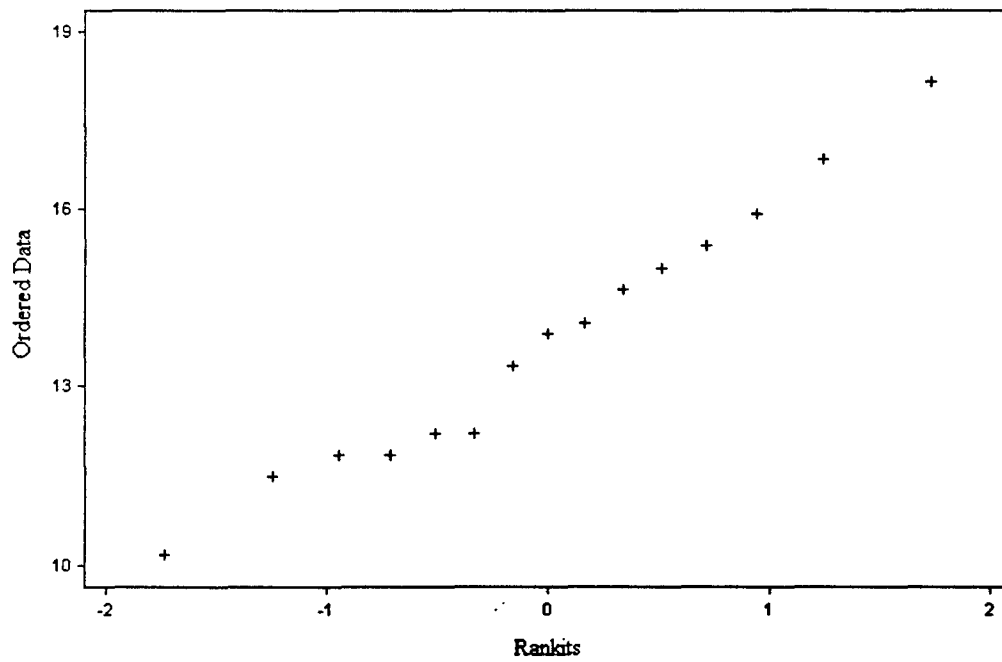
Wilk-Shapiro / Rankit Plot of PSA_TR4
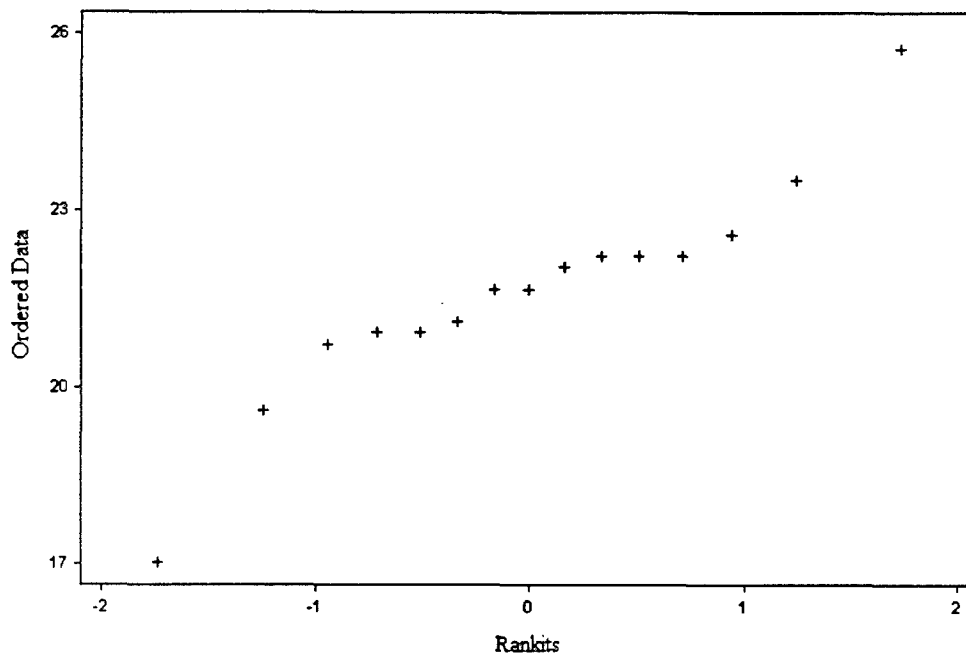
Approximate Wilk-Shapiro 0.8874   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR5
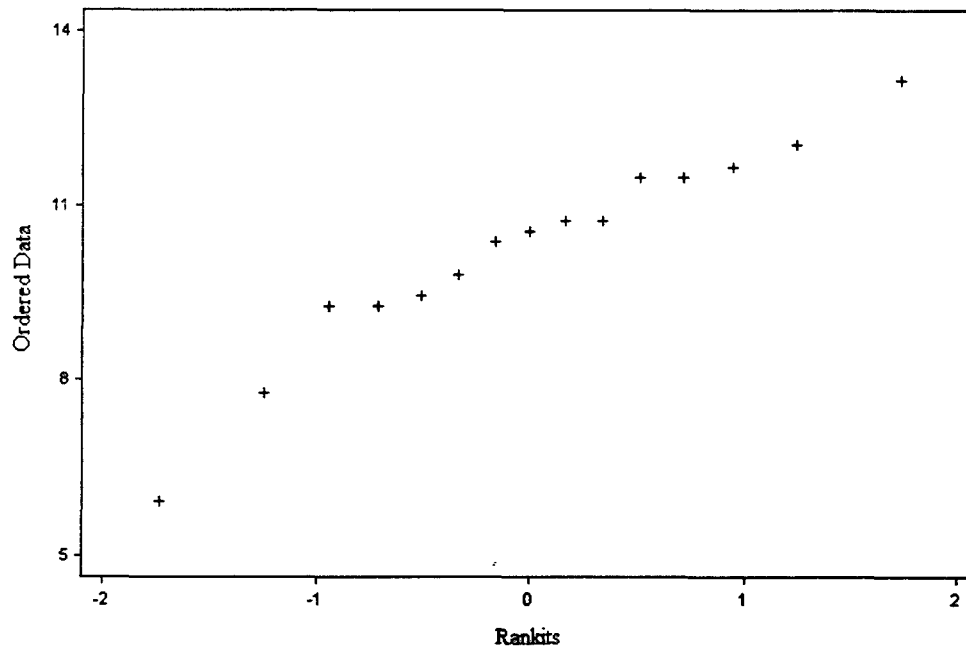
Approximate Wilk-Shapiro 0.9356   15 cases

96

Wilk-Shapiro / Rankit Plot of PSA_TR6
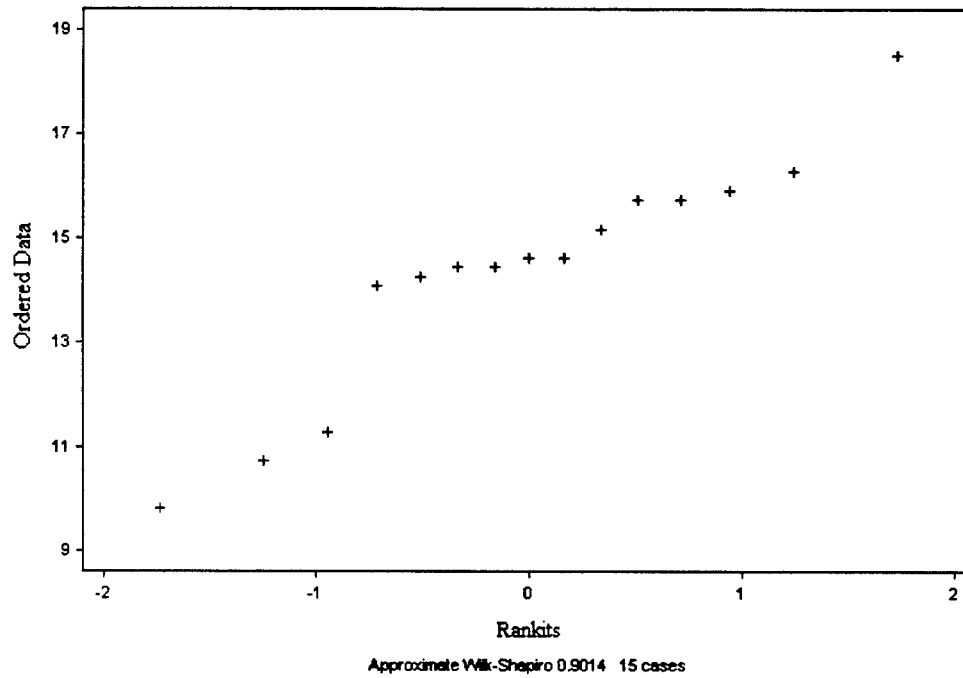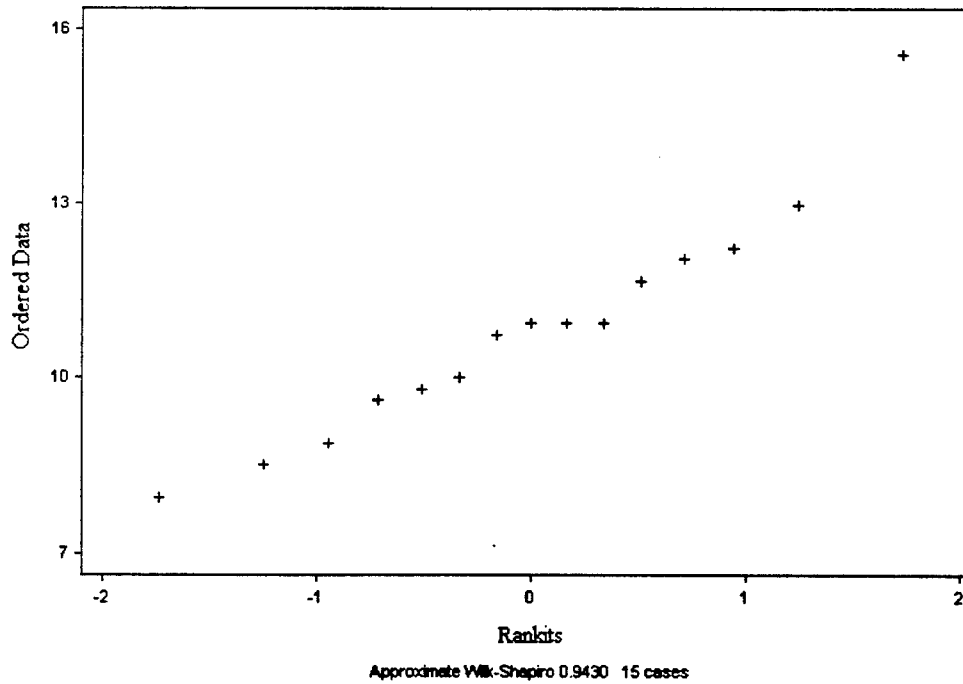
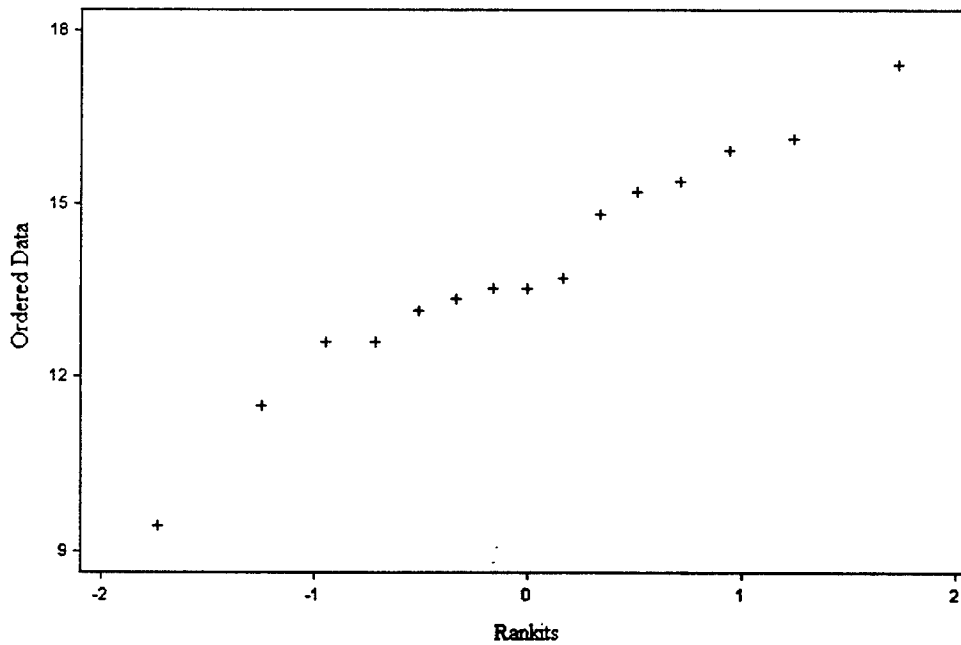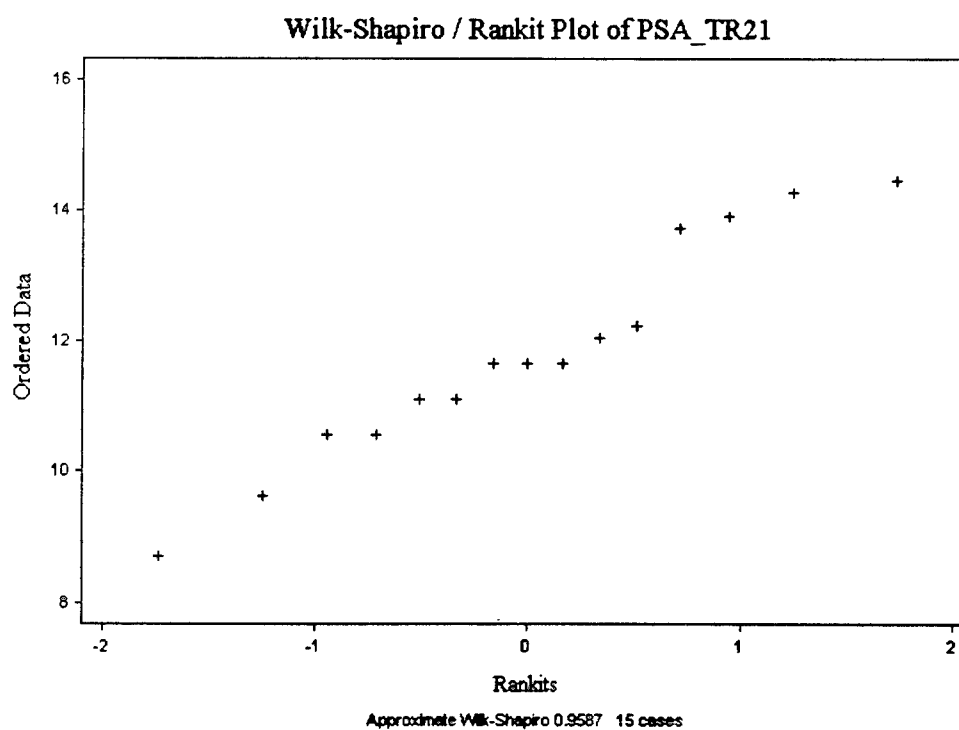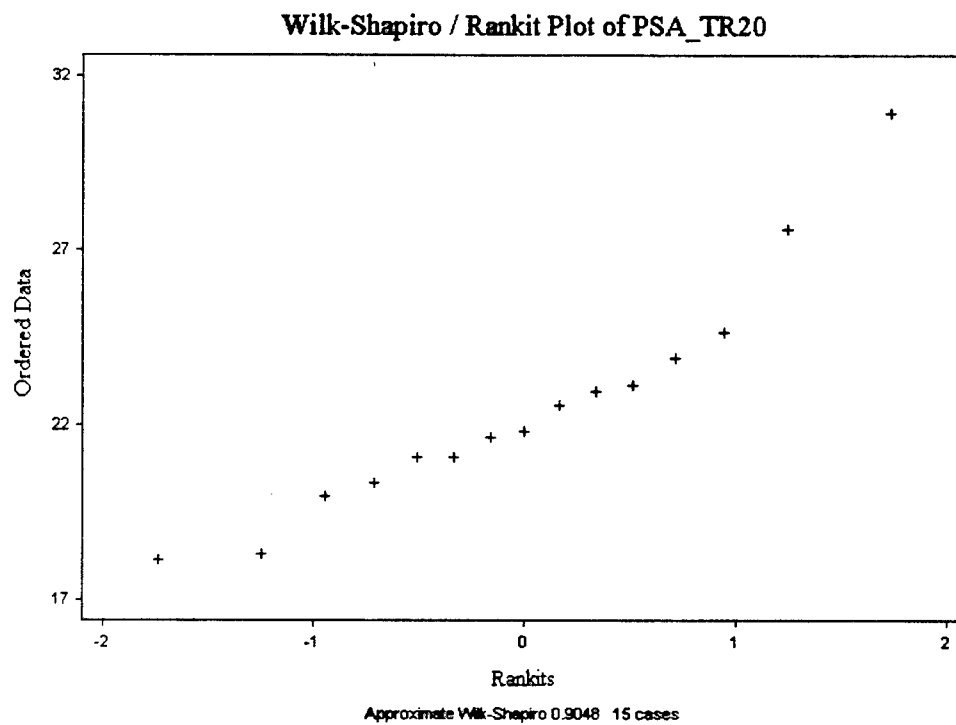Approximate Wilk-Shapiro 0.9014   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR7

Approximate Wilk-Shapiro 0.9430   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR8

Rankits

Approximate Wilk-Shapiro 0.9523   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR9
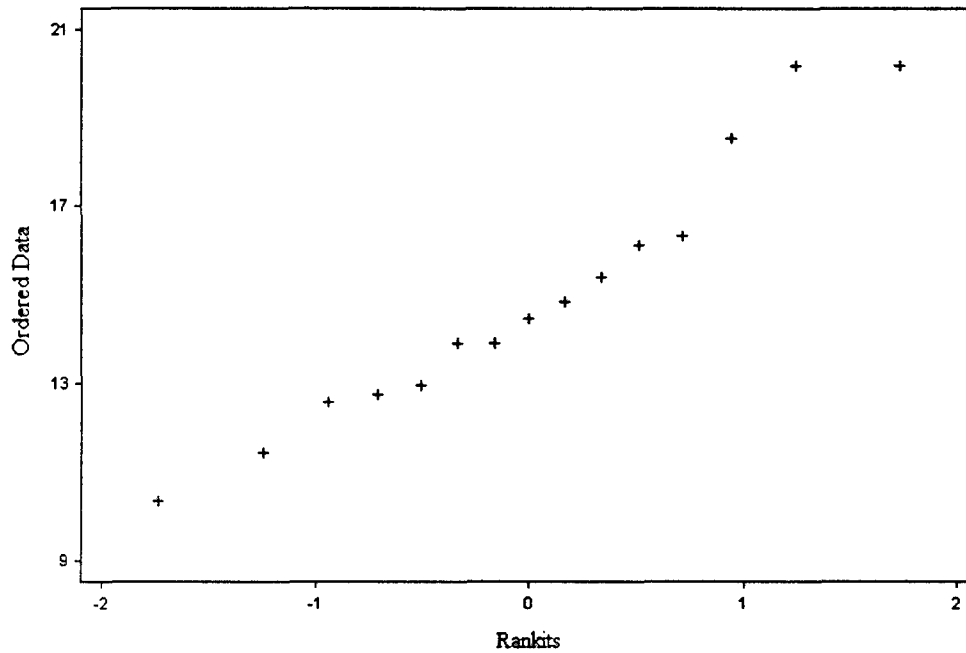
Rankits

Approximate Wilk-Shapiro 0.9358   15 cases
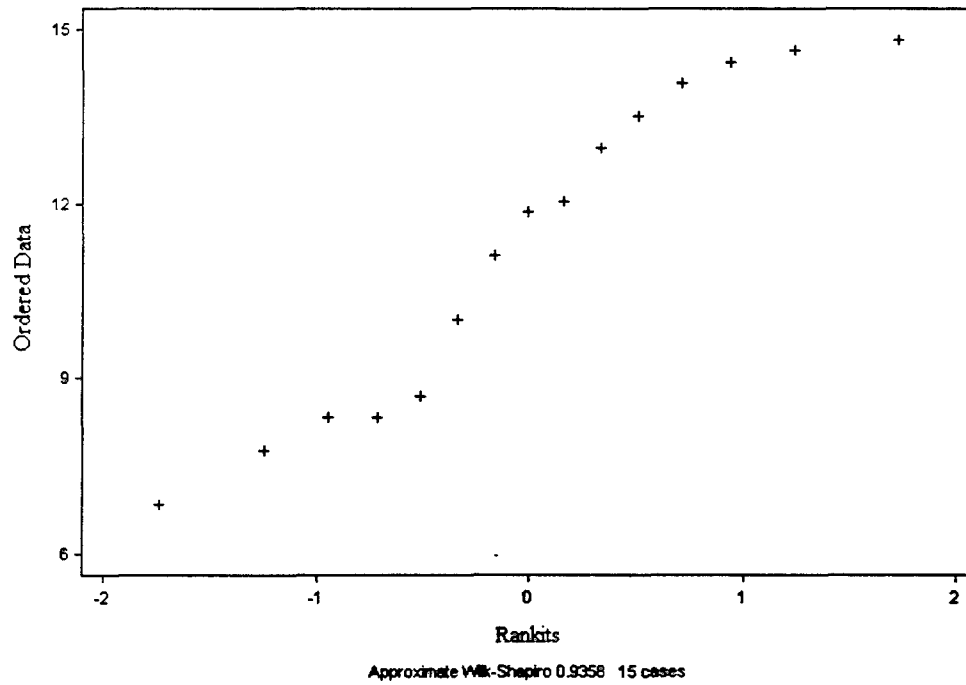
Wilk-Shapiro / Rankit Plot of PSA_TR10
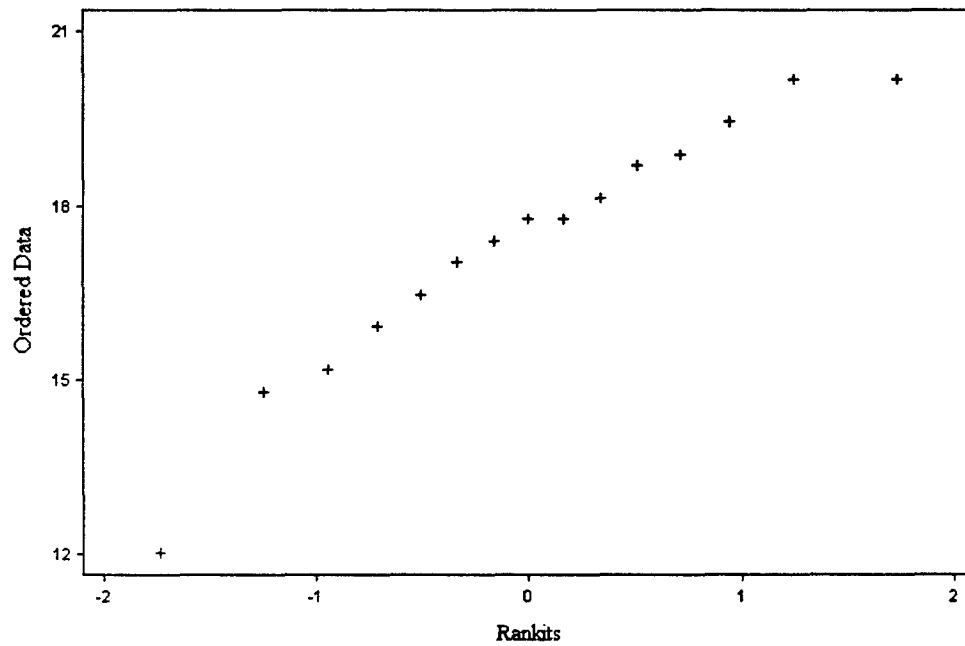
Rankits

Approximate Wilk-Shapiro 0.9422 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR11
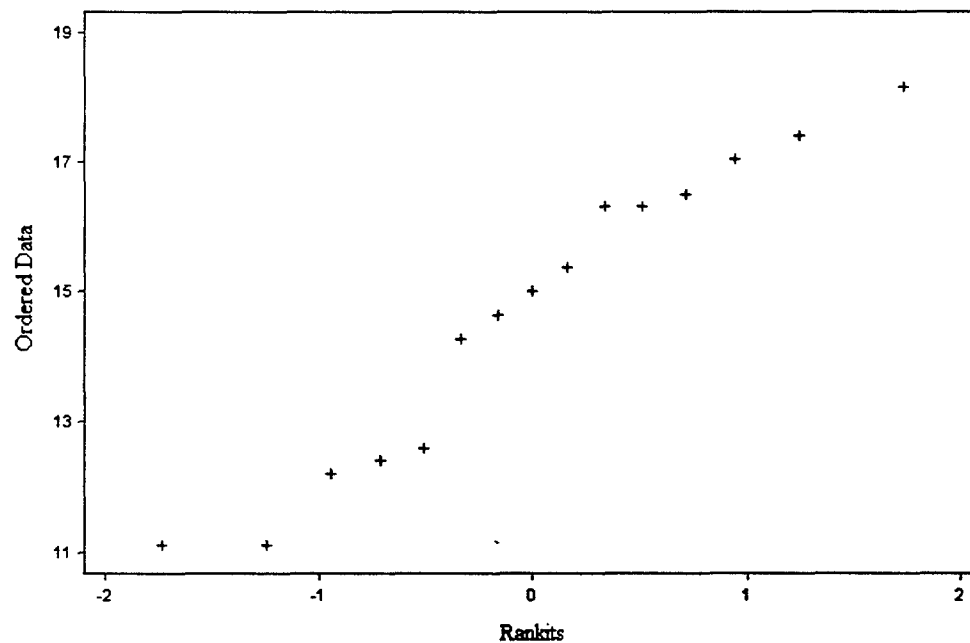
Rankits

Approximate Wilk-Shapiro 0.9525 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR12
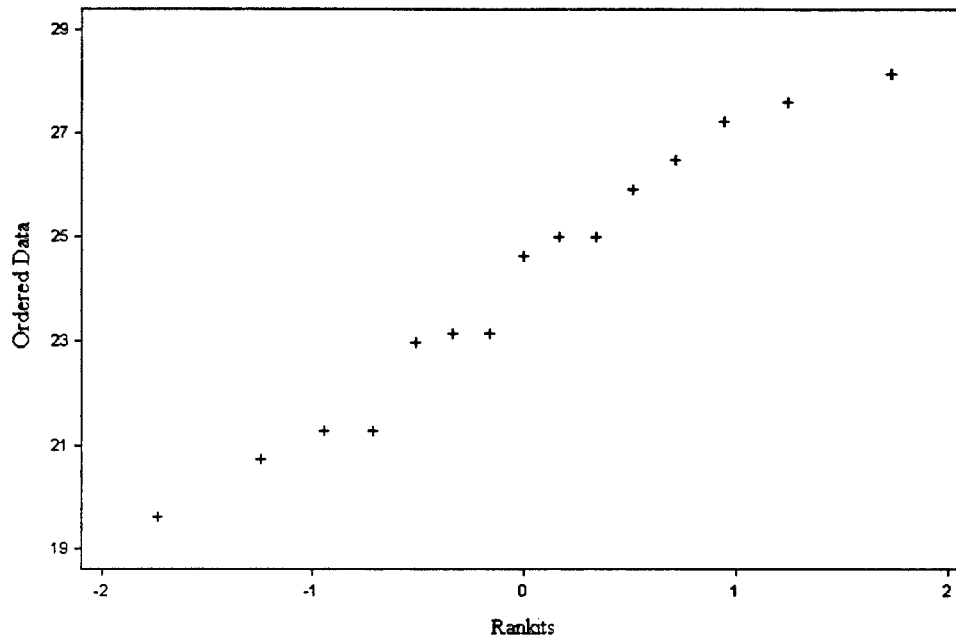
Rankits

Approximate Wilk-Shapiro 0.9723   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR13
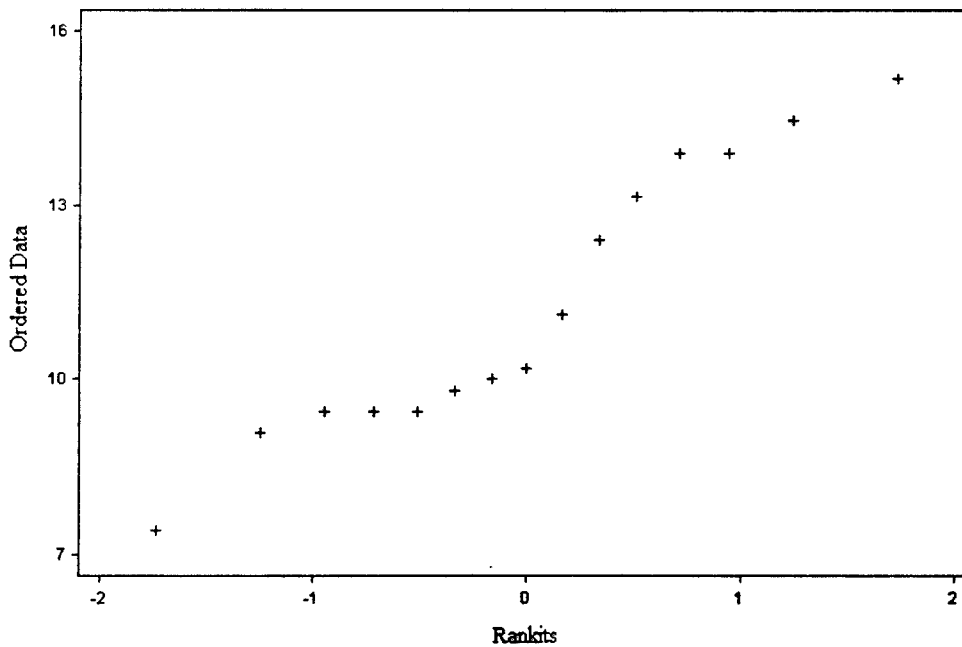
Rankits

Approximate Wilk-Shapiro 0.9299   15 cases
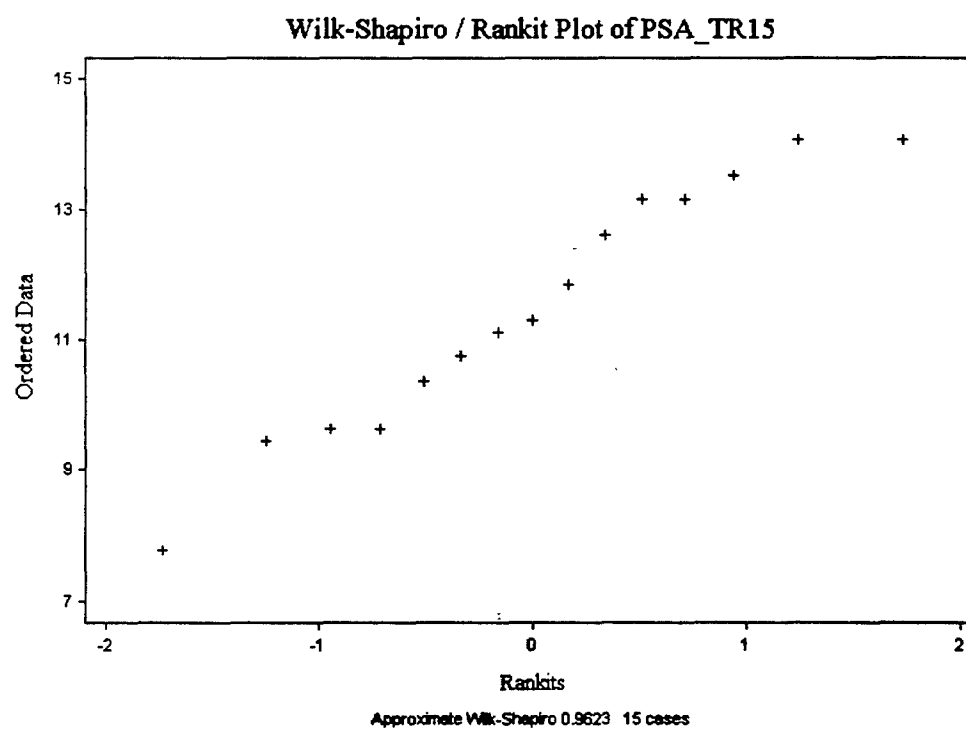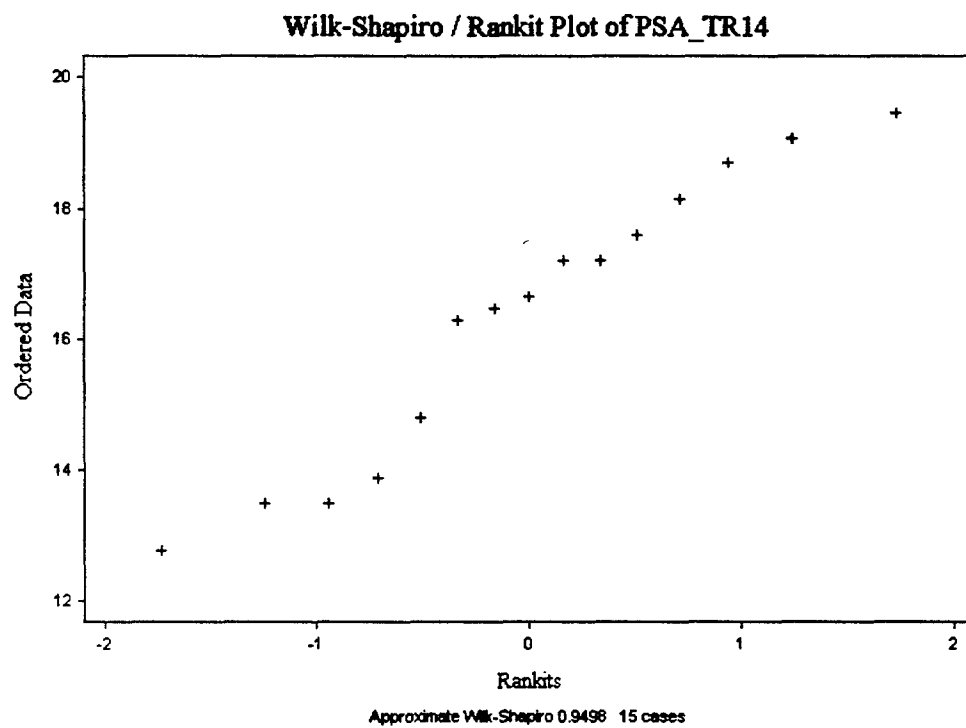
Wilk-Shapiro / Rankit Plot of PSA_TR14

Approximate Wilk-Shapiro 0.9498   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR15
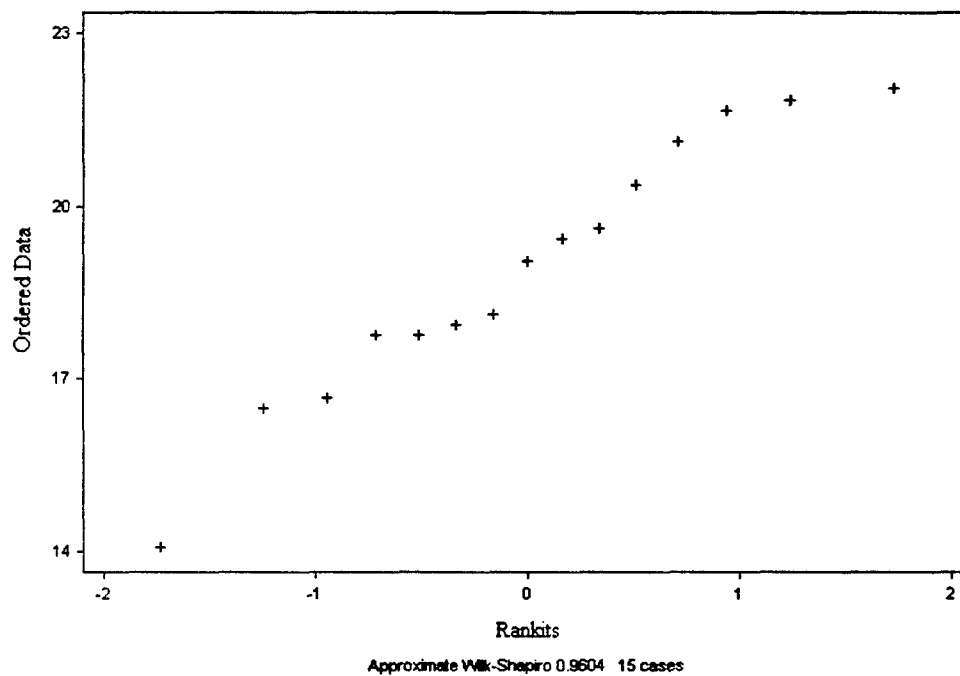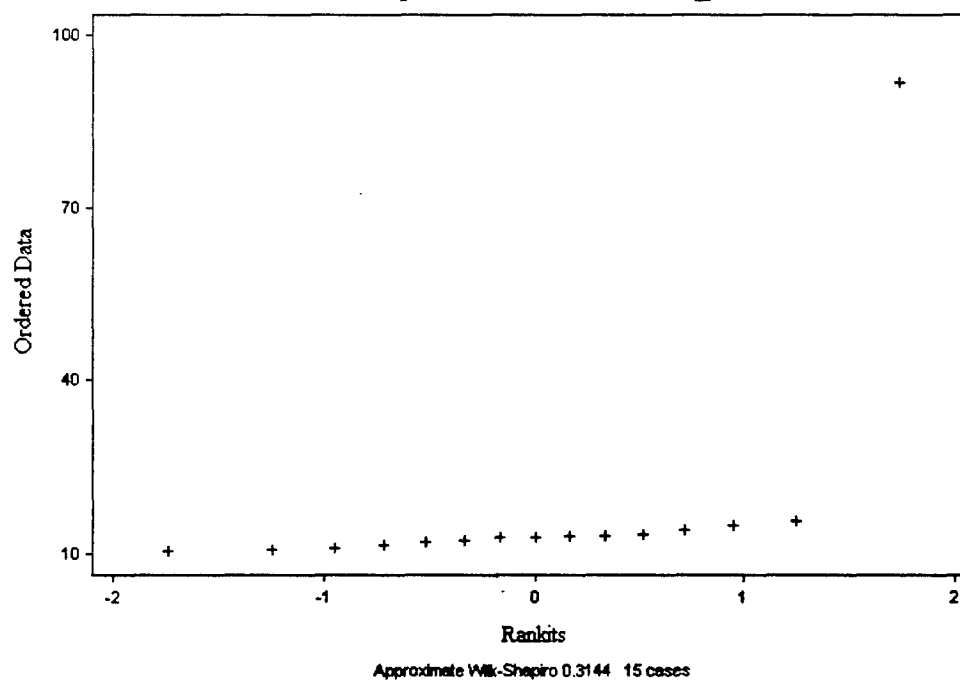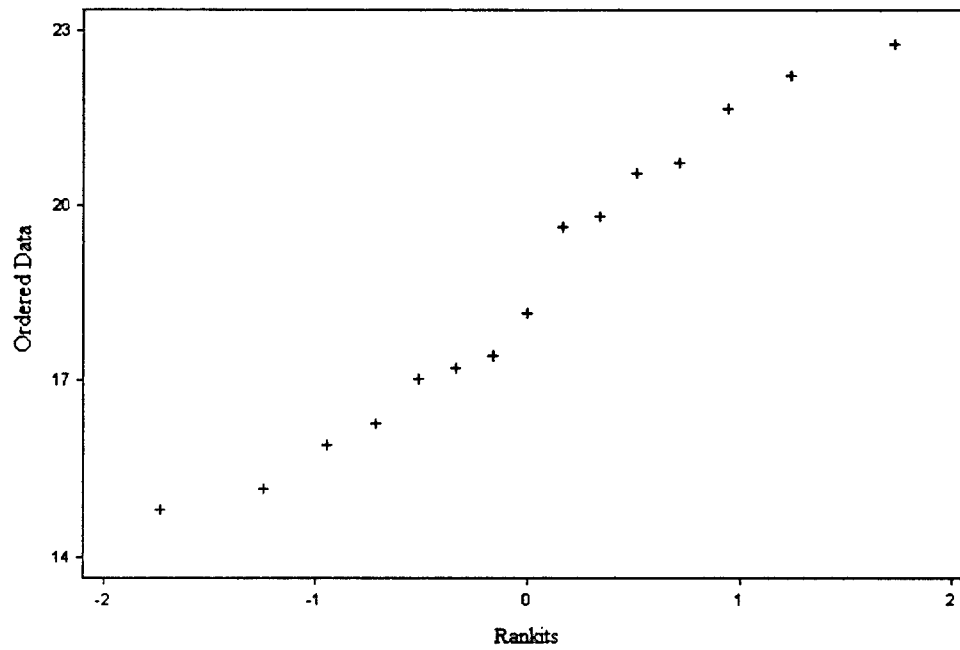

Approximate Wilk-Shapiro 0.9623   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR16

Ordered Data vs Rankits

Approximate Wilk-Shapiro 0.9503   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR17

Ordered Data vs Rankits

Approximate Wilk-Shapiro 0.9474   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR18
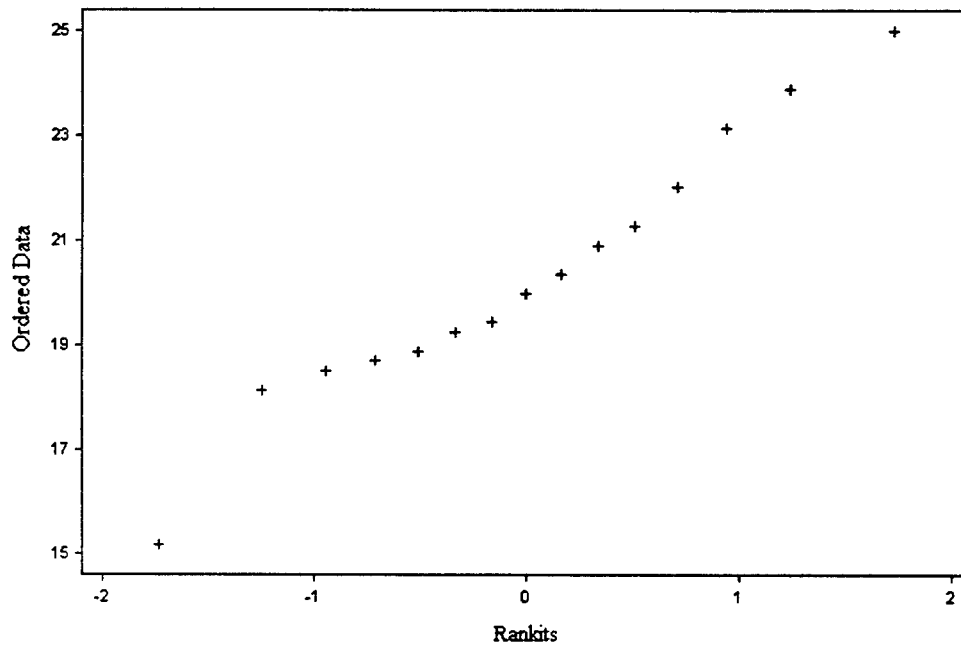
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Wilk-Shapiro / Rankit Plot of PSA_TR19
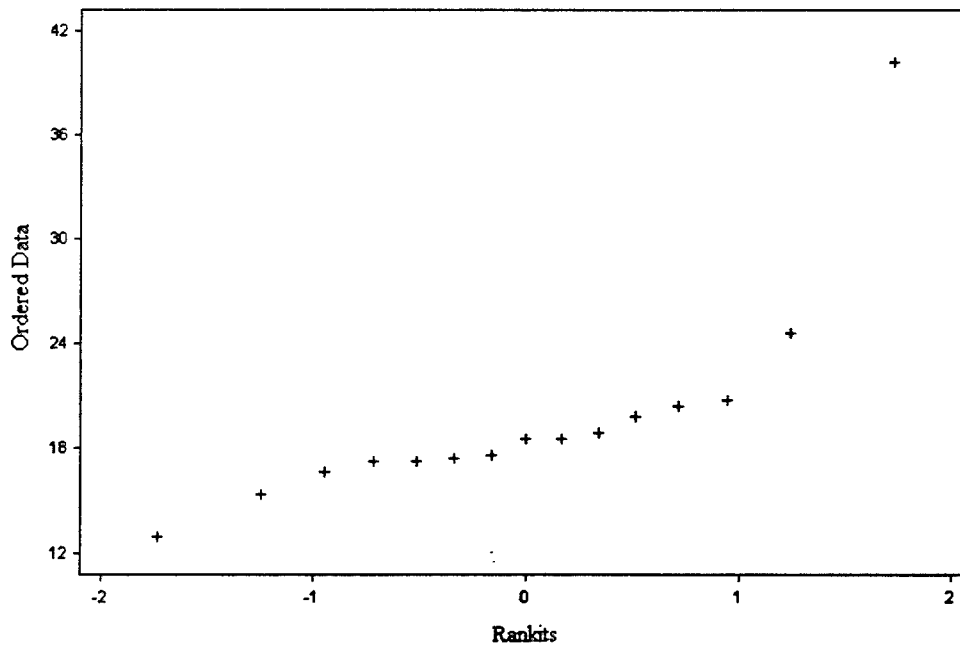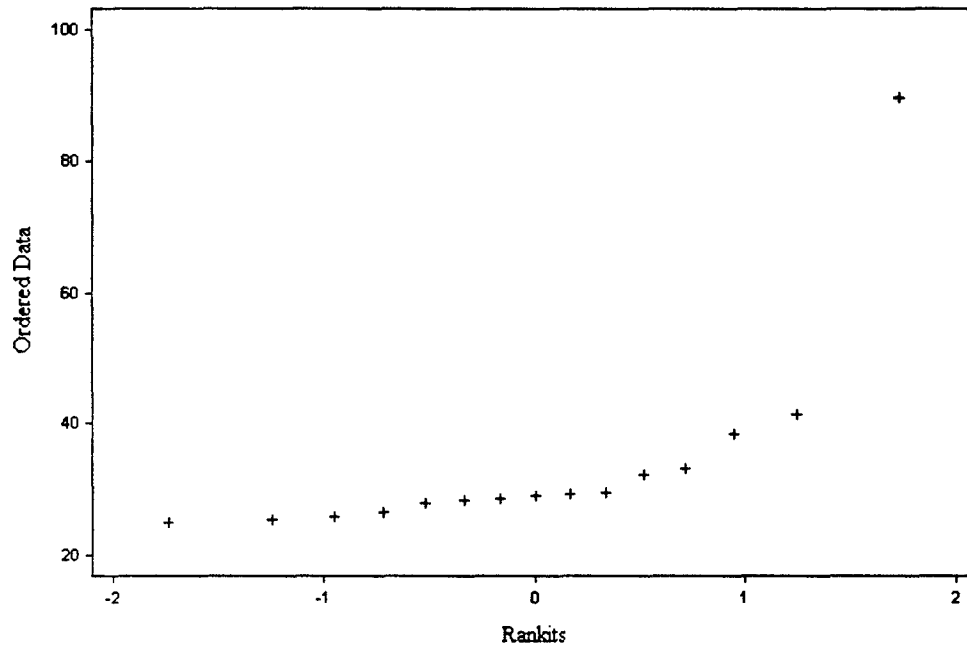
Approximate Wilk-Shapiro 0.9642 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR20

Approximate Wilk-Shapiro 0.9048 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR21

Approximate Wilk-Shapiro 0.9587 15 cases

104

Wilk-Shapiro / Rankit Plot of PSA_TR22

Approximate Wilk-Shapiro 0.9604   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR23

Approximate Wilk-Shapiro 0.3144   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR24

Approximate Wilk-Shapiro 0.9649 15 cases
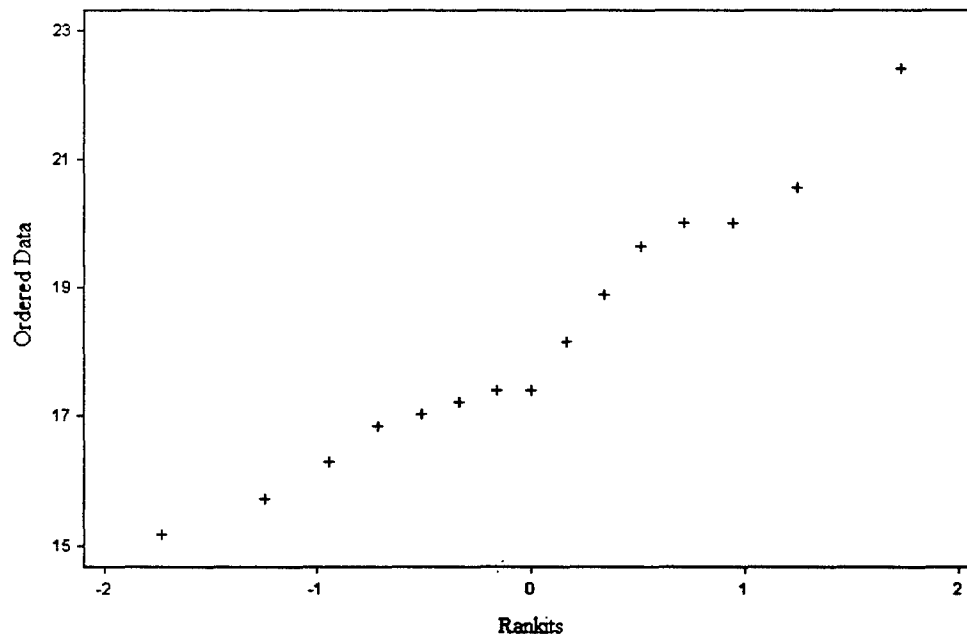
Wilk-Shapiro / Rankit Plot of PSA_TR25

Approximate Wilk-Shapiro 0.6442 15 cases
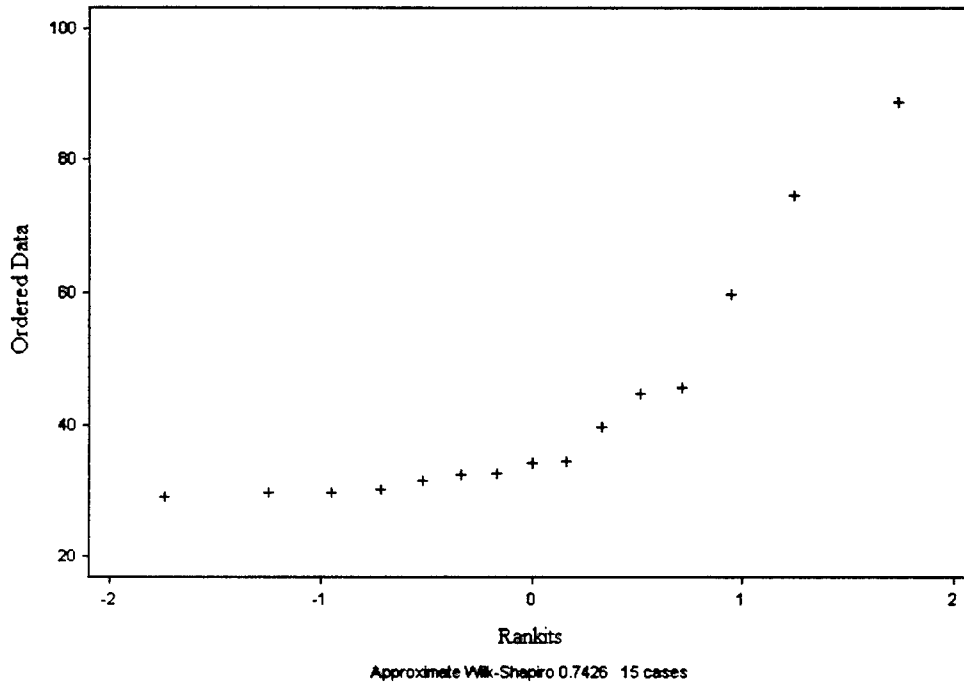
Wilk-Shapiro / Rankit Plot of PSA_TR26

Approximate Wilk-Shapiro 0.4975 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR27

Approximate Wilk-Shapiro 0.9622 15 cases

107

Wilk-Shapiro / Rankit Plot of PSA_TR28

Approximate Wilk-Shapiro 0.7426 15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR29

Approximate Wilk-Shapiro 0.8942 15 cases

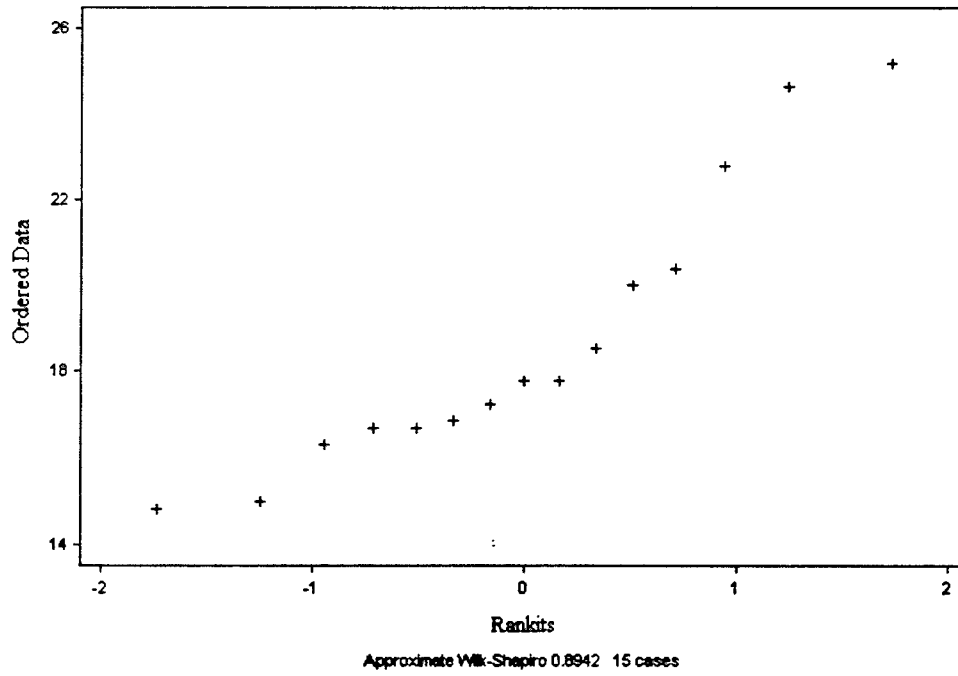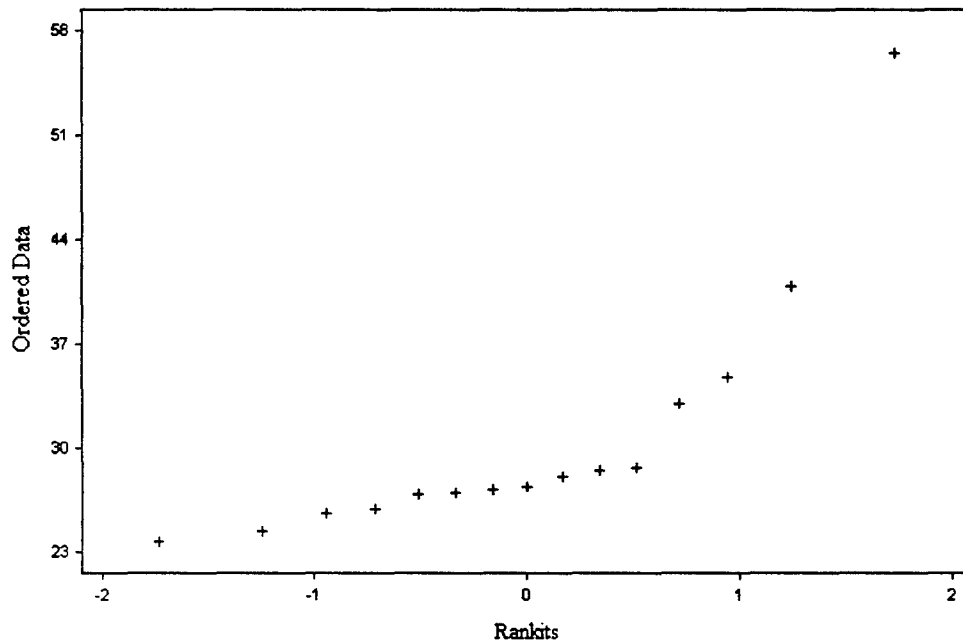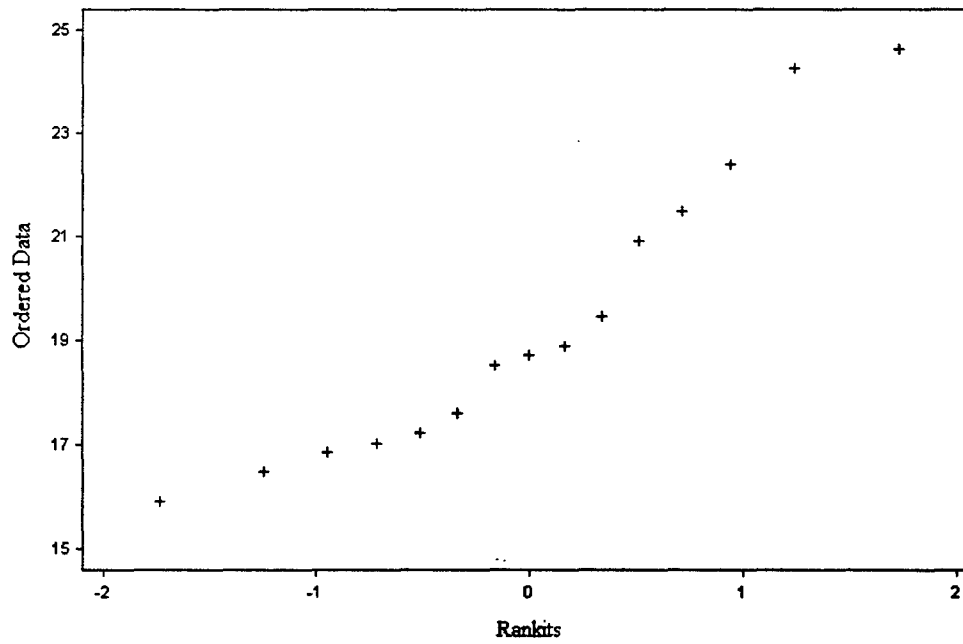## Wilk-Shapiro / Rankit Plot of PSA_TR30

Approximate Wilk-Shapiro 0.6790   15 cases

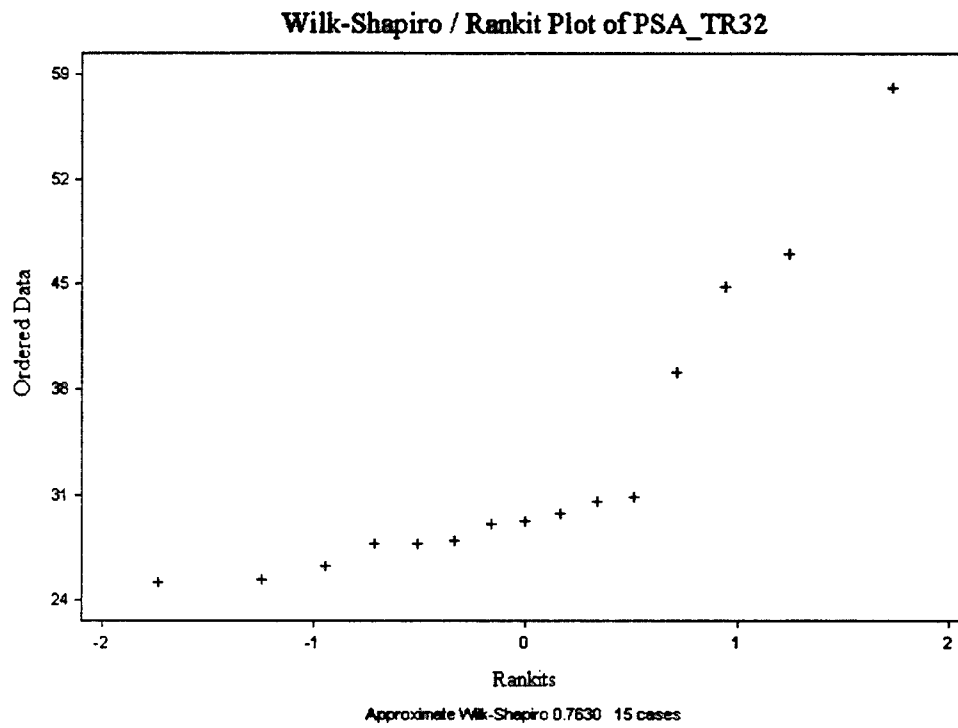## Wilk-Shapiro / Rankit Plot of PSA_TR31

Approximate Wilk-Shapiro 0.9246   15 cases

Wilk-Shapiro / Rankit Plot of PSA_TR32

Approximate Wilk-Shapiro 0.7630   15 cases

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VITA

First Lieutenant Jeffrey D. Havlicek, ████████████████████████ ████████████ graduated from Walsh Jesuit High School in 1989 and entered undergraduate studies at the University of Michigan in Ann Arbor, MI. He earned a Bachelor of Science in Engineering degree in Industrial and Operations Engineering with honors and received his commission on 29 April 1994 through the Reserve Officer Training Corps.

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He became a certified war planner through the Contingency Wartime Planners Course at Maxwell AFB in 1995. In May 1996, he entered the School of Logistics and Acquisition Management, Air Force Institute of Technology, in the Acquisition Logistics Management program. His research interests include logistics modeling, trade study analysis, mobility planning, and supportability testing. His aspirations include a Ph.D. in Operations Management, Operations Research, or Logistics Management.

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13. ABSTRACT (Maximum 200 Words)

The first purpose of this thesis was to study the effects of four factors on F-16 aircraft availability: aerospace ground equipment (AGE) design configuration, mean time between failure (MTBF) of AGE, mean time to repair (MTTR) AGE, and the travel time to transport the AGE around the flightline. A simulation developed by Carrico (1996) that has its foundation based on the Logistics Composite Model (LCOM) was used. ANOVA results indicated that the present estimates of these factors are too broad for trade studies that include an estimate of aircraft availability to begin. The time it takes AGE to travel from one place to another around the flightline strongly affected aircraft availability. It is recommended that further AGE field observation and data collection be accomplished before the merits of one AGE cart technology is compared to another.

The second purpose of this thesis was to collect as much information on the deployability and affordability of AGE as possible. Although much of the information collected was a few years old, the results suggest that new technologies improve the deployment footprint and the combined acquisition and deployment costs.

Background information about support equipment and AGE is included in the study.

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